Water-Energy Nexus 3 (2020) 170–185

Contents lists available at ScienceDirect

Water-Energy Nexus

journal homepage: www.keaipublishing.com/en/journals/water-energy-nexus/

Wastewater resources management for energy recovery from circular economy perspective

Mohanna Zarei

Department of Civil Engineering, University of Kurdistan, 66177-15175 Sanandaj, Iran

A R T I C L E   I N F O

Article history:
Received 29 June 2020
Revised 26 August 2020
Accepted 5 November 2020
Available online 19 November 2020

Keywords:
Wastewater management
Energy recovery
Climate change
Circular economy
Environmental pollutions

A B S T R A C T

To remediate significant risks such as increasing resources consumption, climate change, and environmental pollutions which affect resource management and security, energy recovery from wastewater could be a feasible approach towards the circular economy (CE). Wastewater management for energy recovery creates an exceptional opportunity which bringing environmental, political, economic, and social benefits. Transition to CE addresses many of the wastewater reuse obstacles and energy recovery barriers, from public acceptance to financial and policy management. This review focuses on the energy recovery from wastewater resources as a potential alternative in the CE framework and evaluates different energy recovery technologies. Since decision makers have to address challenges which are more related to the societal, regulatory, and political aspects prior to execute fundamental actions, the practical strategies on implementation of energy recovery from wastewater emphasizing the period of 2010–2020 are proposed. Furthermore, several successful case studies for energy recovery from wastewater as a systematic approach, which cover all potential scenarios are reviewed.

Contents

E-mail address: Mohannazarei@eng.uok.ac.ir

https://doi.org/10.1016/j.wen.2020.11.001
2588-9125/

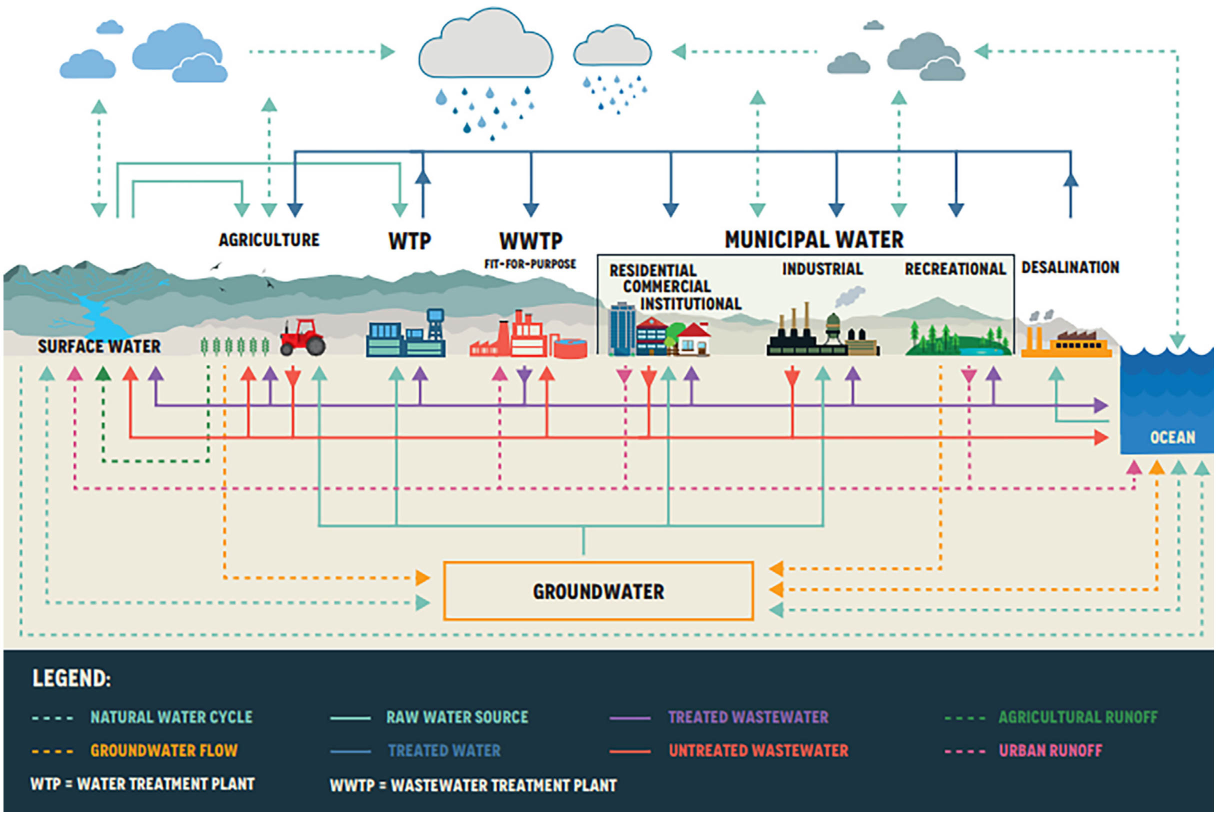

Fig. 1. Wastewater in the water cycle (Source: WWAP (UN Water, 2017)).

1. Introduction

Fresh and clean water scarcity, increasing water consumption, and climate change will affect global water security and will cause crisis in the coming years. This increasing demand of natural resources which merges with global water stress, have highlighted the importance of water as a vital resource that remind the need for extensive adoption of water reuse and recycle. With population growth in urban areas, resources need to be used carefully, recycled, and renewed. Wastewater reuse plays a determining role in case of shortage of conventional resources. Based on scientific reports, water consumption will double by 2050 over the world. Wastewater as an influential component of the water cycle should be managed properly across the entire water management cycle, from freshwater abstraction, treatment, distribution, use, collection, and post treatment to it's reuse and ultimate return to the environment (Fig. 1) (UN Water, 2017). Thus, wastewater treatment for resources recovery is a rational solution to avoid problems derived from droughts and water shortage, especially in countries with water restrictions (Jodar-Abellan et al., 2019).

Based on Somoza-Tornos et al. report, most of wastewater treatment plants (WWTPs) processing wastewater to condition water for disposal, which means meeting the limits given by regulations at a minimum cost (Somoza-Tornos et al., 2019). These WWTPs play a crucial role in a growing market of recycled water in which an increasing number of businesses and public services. From circular sustainability point of view, the urban WWTPs can play a significant role owing to the energy production and resource recovery integration during clean water production process. By Neczaj & Grosser definition, WWTPs are to become "ecologically sustainable" technological systems and developing rapidly due to global nutrient demands, water reuse, and energy recovery from wastewater (Neczaj and Grosser, 2018). The resources and energy recovery from wastewater add remarkable value streams and improve cost recovery and water quality. Resources like cellulose, bioplastics, phosphate, and alginate-like exopolymers from aerobic granular sludge, biochar, biodegradable plastics from polyhydroxyalkanoates accumulated in biomass developing in the wastewater treatment reactors, and biomass can be recovered from WWTPs.

The most important driver behind the circular economy (CE) is resource scarcity. Due to socio-environmental and socio-economic challenges, the CE is gaining attention as a sustainable development component (Geissdoerfer et al., 2017). Governors, policymakers, scholars, and stakeholders preferred the CE concept over current linear economy (Blomsma and Brennan, 2017). Therefore, the CE principles are adopted to reduce raw material consumption, remove waste from material use, and contribute to the sustainable development goals (SDGs) of the United Nations on water and sanitation, once fully operational (Campbell-Johnston et al., 2020; van Leeuwen et al., 2018).

Designing treatment systems with a focus on energy recovery and treatment together are gained attentions in last years, due to increasing global energy demand by approximately 50% between 2010 and 2040 (EIA, 2013). Because of conversion losses and energy-neutral, full capacity recovery of all the energy from wastewater resources may be impractical (Gao et al., 2014). In one critical review article, Kehrein et al. described domestic wastewater cannot fully supply the elemental or energy demands of industrialized societies (Kehrein et al., 2020). However, it does introduce a substantial resource that should be fully applicable in the future. Although several technologies for the recovery of water, energy, fertilizer, and other products from wastewater have been explored in the academic arena and research institutes and few of these have been applied on large scale due to technical immaturity and non-technical limitations. Kehrein and coworkers identified nine bottlenecks based on scientific literature that may cause some delays in successful implementation of this process which are as follows: economics and value-chain development (process costs, resource quantities, resource quality, market value, application and distribution), environmental emissions, health risks, social acceptance, and policy issues. In the case of energy recovery from wastewater, recovery process could cause extra costs due to excessive operational and investment costs. Geographical and temporal variations between supply and demand, lack of infrastructure, and cost issues are challenging factors for off-site recovered energy. Therefore, by designing organized and balanced system (supply, distribution, and transport) the situation could be mitigated. Also, the fatal risks to human health due to contaminants and environmental problems of recovery process should not be underestimated. The main challenge for energy recovery is lack of the integrated system for operating existing wastewater treatment plants to considering wastewater as a resource that requires management at different levels. Further, investments and development in research in order to present recovered resources successfully into markets for societal consumption are required. Attracting the interests of all stakeholders, including business partners, end-users and policymakers which are integrated into the planning process, and applications with unique selling propositions is imperative. Thus, the feasible management of potential challenges and the finding of partners along a value chain to share the risks associated with pioneering is required for successfully implementing wastewater resource recovery (Kehrein et al., 2020). Successful implementation of energy recovery processes from wastewater needs effective policy and legal frameworks.

The main objective of this review is to provide an overview on wastewater treatment and management for energy production from CE point of view. Also, this review aims to provide a clarity for the water-energy nexus approach in the specific context of wastewater resources. We started by evaluating the current status of wastewater resources management around the world. Then, we discussed the importance of resources recovery from wastewater with their economic capacities and potentials to overcome resources scarcity challenges by efficient solutions especially in the CE concept. We mentioned various resources which recover from wastewater treatment, their productivity, their part in water-energy-economic cycle, and the challenges of these approaches in CE context. This review focuses on the energy recovery from wastewater resources in the management framework and discusses challenges which are more related to the societal, regulatory, and political aspects emphasizing the period of 2010–2020. Therefore, this review provides challenges, benefits, and future opportunities for development leaders, scientific communities, and stakeholders for better decision-making, sustainable development, and efficient cooperation.

2. Overview of wastewater resources management around the world

An integrated management of energy, food, and water resources by a holistic approach could help address several of the biggest global challenges, such as climate change, environmental and social security, and economic development which pose critical pressures in providing water, energy, and food security at the global scale (Zarei, 2020a, 2020b). Widespread global industrial activities have generated severe impacts on the environment through air and water pollution and generation of large amounts of waste materials (Zarei et al., 2019). In this case, the increasing demand for recovery of the resources contained in wastewater, such as nutrients, energy, and water as an eco-friendly approach for wastewater resources management is highlighted (Leyva-Díaz et al., 2020). Wastewater management as SDG 6 in one of the 17 SDGs with focus on drinking water and basic sanitation to cover the entire water cycle, including the management of water, wastewater, and ecosystem resources expands the Millennium Development Goals (MDGs) and is dedicated to water and sanitation and sets out to "ensure availability and sustainable management of water and sanitation for all". It is clear, the vast majority of wastewater is neither collected nor treated and the UN reported in 2017 that over 80% of the wastewater worldwide is still discharged without appropriate treatment (UN Water, 2017). In comparison to water resources challenges, wastewater management is received little social and political attention. Although, ignoring wastewater management will induce negative impacts on the sustainability of water supplies, human health, economy, and environment. Nowadays the wastewater management is a norm in several countries, but based on environmental performances and economical aspects, still there are open conversations about the type of treatment approach to be adopted. Water reuse and wastewater treatment have considered as efficient alternatives for water supply, due to the harsh water stress in some regions of the world, which water demand exceeds water supply, and expensive requirements are needed to remove pollutants and emerging contaminants (Voulvoulis, 2018). Fig. 2a shows global freshwater withdrawals consumption and produced wastewater by major water use sector, and global water reuse by application after advanced treatment. Owing to the various approaches and roadmaps for wastewater treatment, the required steps to achieve SDGs, will pose a higher financial burden on low-income and lower middle-income countries (Fig. 2b), compared to high-income and upper middle-income countries (Sato et al., 2013). Sato et al. believed there is a synergy between country's level of industrial and municipal wastewater treatment and the income level. High-income countries treated about 70% of the wastewater they generate, while the treatment percentage in upper middle-income countries, lower middle-income countries, and low-income countries are about 38%, 28%, and 8%, respectively (Sato et al., 2013). Specifically, the rate of municipal and industrial wastewater treatment in Europe, Middle East and North Africa (MENA) region, and Latin American countries are estimated about 71%, 51%, and 20%, respectively. While, African countries are limited by poor financial resources for the developed wastewater management and 32 out of 48 Sub-Saharan African countries had no data available on wastewater generation and treatment (Sato et al., 2013). The huge amount of untreated wastewater discharged into the environment can be attributed to the low eagerness to pay for this kind of service. Thus, a significant focus should be given to all of the technologies which are able to reduce the treatment costs and improve performances in the long term.

Wastewater management including safe reuse of water and recovery of vital resources, introduces remarkable opportunities for commercial markets. Recently, nanomaterials gained significant attentions for widespread applications in biosensing, water splitting, energy recovery, environmental remediation, and wastewater treatment (Kadam et al., 2020; Wang et al., 2020; Zarei, 2020a, 2020b; Zarei and Aalaie, 2019). The World Bank Water Global Practice report sheds a light on wastewater management experiences in the Latin America and Caribbean region for 2020, which are already reaping benefits. For example, (1) by using treated wastewater instead of groundwater, the San Luis Potosi power plant in Mexico cut costs by 33%, leading to 18 Million US dollars in savings over six years for the power utility (for the water utility, the additional revenue from selling treated wastewater helped cover operations and maintenance costs), (2) a wastewater treatment plant in Cusco, Peru, saves 230,000 US dollars a year in transporting biosolids and landfill fees due to an agreement with the local compost producer (the compost produced with the plant's

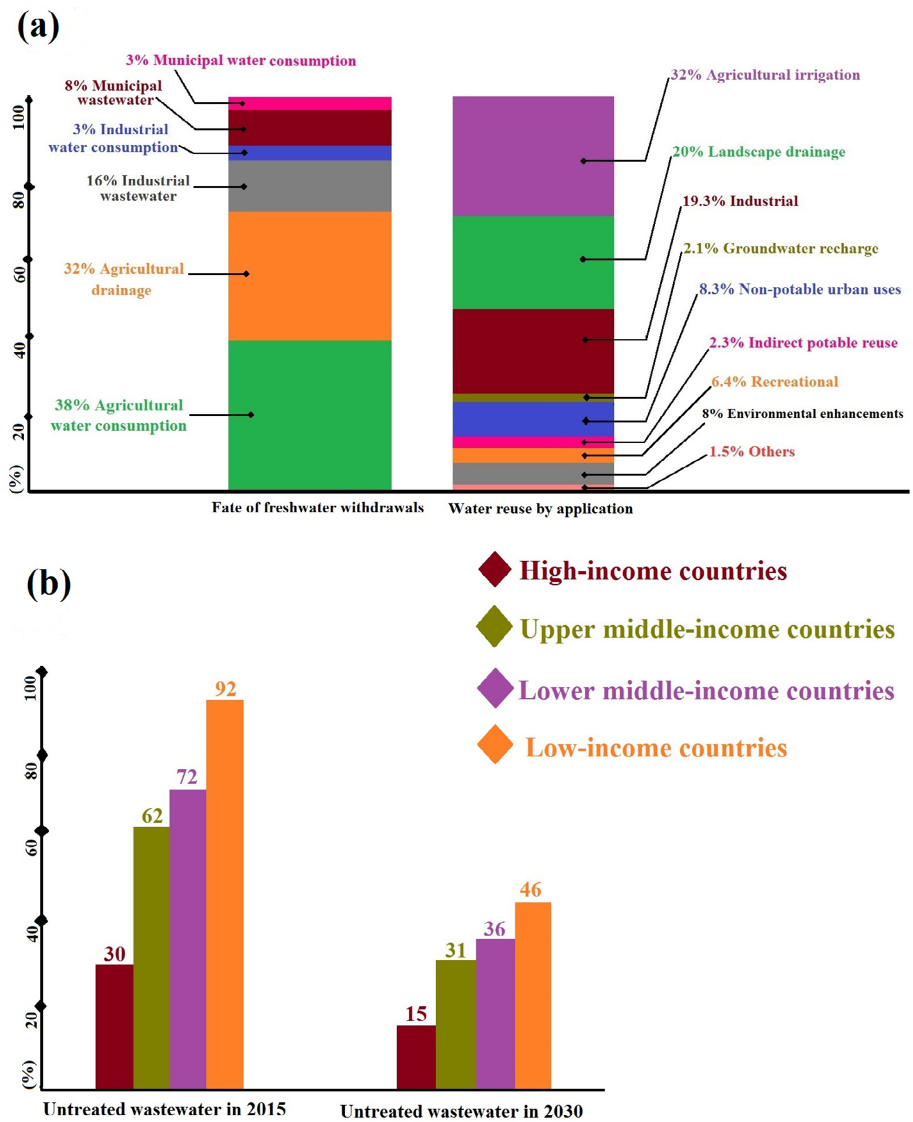

Fig. 2. a) Global freshwater withdrawals consumption and produced wastewater by major water use sector, and global water reuse by application after advanced treatment, b) Percentage of untreated wastewater in 2015 in countries with different income levels and aspirations for 2030 (Source: AQUASTAT database Contributed by Sara Marjani Zadeh (FAO), and (Mateo-Sagasta et al., 2015; Sato et al., 2013; Shiklomanov, 1999; UN Water, 2017)).

biosolids is then used as part of the water management project to preserve the Piuray Lake), (3) the Brazil-based water and wastewater utility's use of biosolids for corn production led to higher-than-average grain yields and was 21% more efficient than mineral fertilizers, (4) the operator of the La Farfana wastewater treatment plant in Santiago, Chile, after investing 2.7 Million US dollars to retrofit the plant, was able to sell biogas, accounting for an annual net profit of 1 Million US dollars for the business. In the CE framework, economic development is correlated with the saving of resources and environmental sustainability. The CE concept could fabricate notable synergies for the resource recovery as a central element to a CE approach and offers a strategy to improve water supply by sustainable wastewater management. Relationship between CE principles and water systems management is shown in Fig. 3. As one of the most critical challenges for future sustainable development of wastewater as a carrier of essential resources which can be converted to marketable products, the CE approach can guarantee the water reuse safety, and apply water quality standards adopted to the specific use and economic purposes (Masi et al., 2018).

3. Resources recovery from wastewater

Due to the diverse sources and contained components, wastewater flows can operate differently for resources recovery purposes. Fig. 4 provides an overall overview of the main wastewater flows, from their generation at the source to their ultimate fate. Uncollected wastewater finally finds it's way into the aquatic environment (UN Water, 2017). Owing to the human activities and contaminated water resources, microbial pollutions posed a huge threat to the global public health (Mohammad Zarei and Zarei, 2018). The treated wastewater can be reused for multiple purposes such as industrial sectors, agricultural purposes, irrigation, groundwater replenishing and by effluent quality improvement, it can also use for domestic use, fire protection, car wash, and toilet flushing. Also, as a consequence the higher quality of river waters used for drinking water (Becerra-Castro et al., 2015). The impact of energy production on water resources demand is obvious, especially when it coupled with climate change. In this case, Yuanchun Zhou et al. developed a study on a Long-range Energy Alternatives Planning System (LEAP) model combined with plant-level data to

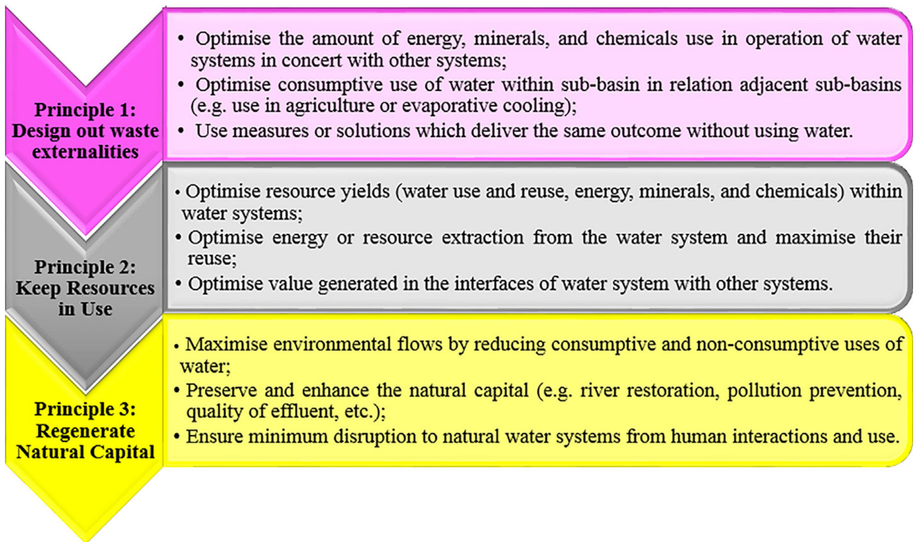

Fig. 3. Relationship between CE principles and water systems management (Source: White Paper, Ellen MacArthur Foundation 2018).

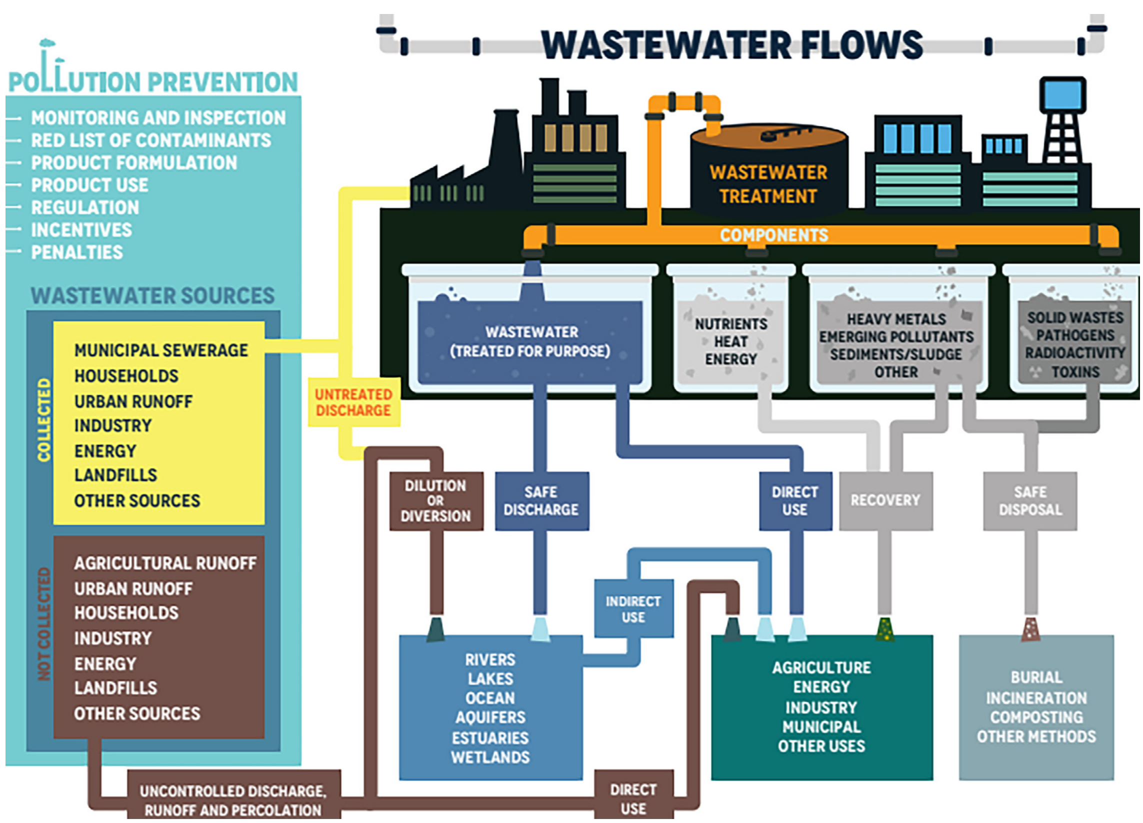

Fig. 4. Wastewater flows and sources (Source: WWAP (UN Water, 2017)).

study the impact of energy policies on water resources management for one of the most developed provinces in China, Jiangsu province which is facing both energy and water stresses (Zhou et al., 2019). The European Union officially acknowledged wastewater resources for energy recovery in 2018. In the last decades, the rate of waste production is increasing over time and it is environmentally unsafe, due to emission of greenhouse gases (GHGs). Therefore, in order to reduce GHGs emissions from wastes it is essential to use approaches such as wastewater heat recovery that can convert wastes to energy in environmentally-friendly way. Based on the recent study by Ahmed et al. using tools like modeling, remote sensing (RS), geographical information system (GIS), unmanned aerial vehicles (UAVs), and life cycle assessments (LCA) can be helpful for quantification of the impacts of waste management techniques on ecosystem (Ahmed et al., 2020). Also, Spriet et al. proposed a three-step methodology for a case study in the Ireland, including (1) an energetic analysis at the WWTP, (2) a spatio-temporal analysis of supply and demand in potential supply areas, and (3) an integrated analysis, overlaying the supply and demand profiles which allows to account for both the proximity of consumers and potential temporal mismatches between supply and demand (Spriet et al., 2020).

Based on report by Lyu et al., Florida State (Southeastern region of the United States) as the leading state in urban reuse and wastewater treatment, used more than 45% of its treated wastewater resources for irrigation (Lyu et al., 2016). The interesting point in reuse of treated wastewater for land irrigation relates to it's potential to reduction of local water stress. Also, nutrients contained in the wastewater play an important role as commercial fertilizers.

Nutrient as one of the main elements of wastewater resources and nutrient recovery as a promising strategy at WWTPs are rapidly embraced by different parties, due to the potential of move towards a sustainable society and enabling environment, decreasing the demand of fossil-based fertilizers and reducing the consumption of scarce resources based on the CE principles. Nutrients can be recovered from different resources such as raw wastewater, semi-treated wastewater streams and sewage sludge (Zhang et al., 2017). Currently, technically recovered phosphorus from WWTPs in Europe is undeniable which leads to eutrophication (Kabbe et al., 2015). Batstone and coworkers suggested urine separation from the main wastewater stream as another option for nutrient recovery which can be theoretically recovered on the level of 70% using the urine-collecting system in toilets (Batstone et al., 2015). In this case, it is estimated that about 70–80% of nitrogen and 50% of phosphorus is contained in urine. Also, nutrients recovering through aqua-species is an eco-friendly technology which reduces energy demand by utilizing these compounds in wastewater and then can be used as fertilizers or animal feeds, and amazingly there is a synergy between wastewater treatment and nutrient recovery (El-Shafai et al., 2007). In the case of nutrients, the type and properties of wastewater depending on the selected technology impact on recovered materials quality and treatment costs and there is no single optimal practical solution for all the situations. Thus, more researches are needed to improve process efficiency and increase their economic viability (Robles et al., 2020). Despite of the challenging situation, several benefits of nutrients recovery are still remain such as prevention of eutrophication in aquatic environments, preparing a potential fertilizer for agricultural applications, and commercial value which reducing the dependence on inorganic fertilizers derived from phosphate mining and diminishing the energy demand for chemical fertilizer production (Melia et al., 2017).

The application of sewage sludge obtained from wastewater resources treatment in the different industries fits perfectly into the CE principles. In a comprehensive study, Bolognesi et al. discussed on properties of biochar as an obtained resource from sewage sludge at WWTPs which is one of the most exciting final products from wastewater treatment (Bolognesi et al., 2019). They believed, besides the widespread options for sewage sludge disposal, a potential process for sustainable resources recovery from this residue is it's conversion into biochar. Also, construction materials such as brick, tile, cement, concrete, mortal, and lightweight materials can be produced from sewage sludge. Smol et al. reported the possibility of recovering strategic elements with economic benefits such as copper, silver, and gold from the ashes that remain after burning sewage sludge (Smol et al., 2015). Also, the process of wastewater treatment using biological fuel cells can be useful for produce electric power (Pandey et al., 2016). As another research outcome, biodegradable plastics can be generated from polyhydroxyalkanoates accumulated in biomass developing in wastewater treatment reactors (Bengtsson et al., 2017). The main challenges associated with reuse of treated water still remains such as very high effluent quality requirements, expensive operational cost, risks to human health, high cost of dual systems for the reclaimed water delivery, and the lack of social acceptance (Neczaj and Grosser, 2018). The overview of different technologies and processes used for resources recovery from wastewater with their advantages and disadvantages is presented in Table 1.

Table 1
The overview of different technologies and processes used for resources recovery from wastewater with their advantages and disadvantages.

Process	Resource recovered	Advantages	Disadvantages	Reference
High-value added products				
Adsorption	Polyphenols	High percentage of recovery, and use of biodegradable and natural coating agent.	Regeneration or substitution of the activated carbon.	(Yangui and Abderrabba, 2018)
Cloud Point Extraction	Polyphenols	Biodegradable nature of the extractants.	High consumption of chemicals.	(Kiai et al., 2018)
Precipitation	Proteins/Lipids	High percentage of protein recovery and low temperature.	High consumption of chemicals and acidic pH.	(Kurup et al., 2019)
Complexation	Proteins	High percentage of recovery and use of biodegradable complexing agents.	High consumption of chemicals.	(Li et al., 2019)
Extraction	Phenols	High percentage of recovery.	High consumption of chemicals.	(Guo et al., 2018)
Nanofiltration	Active pharmaceutical ingredients	High recovery, simple operation, and low operating costs.	Short membrane lifetime and membrane fouling and cleaning.	(Shahtalebi et al., 2011)
Nutrients				
Crystallization	Phosphorus	High degree of recovery, very high efficiency as fertilizer for acidic soil, and high for alkaline soil.	High consumption of $MgCl_2$, high operating costs, decrease in the acidification potential, and high consumption of $Mg(OH)_2$.	(Amann et al., 2018; Guerra-Rodríguez et al., 2020)
Precipitation	Phosphorus	High degree of recovery.	High consumption of MgO and high operating costs.	(Desmidt et al., 2015; Guerra-Rodríguez et al., 2020)
Precipitation/ Crystallization	Phosphorus	High degree of recovery and very high efficiency as fertilizer for acidic soil and high for alkaline soil.	High consumption of $MgCl_2$, high operating costs and decrease in the acidification potential.	(Amann et al., 2018; Desmidt et al., 2015; Guerra-Rodríguez et al., 2020)
Ion-exchange	Phosphorus/ Nitrogen	High degree of recovery and simple operation.	Regeneration of the resins and high consumption of NaCl.	(Johir et al., 2011)
Adsorption with Clinoptilolite (zeolite)	Phosphorus/ Ammonium/ Potassium	High to moderate degree of recovery and simple operation.	Regeneration or substitution of the zeolite.	(Kocatürk-Schumacher et al., 2017)
Urine separation	Phosphorus/ Nitrogen	High degree of recovery.	High operating costs.	(Batstone et al., 2015)

3.1. Waste-to-energy supply chain

Waste management, materials recycling, climate mitigation, and GHG emissions reduction are targeted by political agendas, due to rapid population growth, energy demand, and increasing waste amounts (de Sadeleer et al., 2020). For this purpose, the waste-to-energy (WTE) supply chain could be a practical method towards CE. Pan et al. discussed several outstanding WTE technologies including combustion, gasification, and anaerobic digestion. Also, they proposed the strategies on implementation of WTE supply chain to overcome the challenging barriers from the aspects of technology, finance, institution, public concerns, and regulation (Pan et al., 2015). As a case study, Lam et al. developed a green strategy for systematic design of waste-to-energy supply chain for the Peninsular Malaysia. This two-stage model including (1) Micro-stage, the optimization and allocation of waste (e.g., biomass, industrial waste, etc.), as well as the design of integrated processing hub and (2) Macro-stage handles the synthesis and optimization of waste-to-energy supply network (Lam et al., 2013). Also, Mohammadi and Harjunkoski proposed a mixed-integer linear programming model for a waste supply chain problem, which maximized the generation of fuel and energy from the waste feedstock and optimized the selection of waste conversion technologies, considering their economic and environmental impacts (Mohammadi and Harjunkoski, 2020). The results provided an analysis of the economic value of the waste supply chain operations and present sustainable solutions for waste treatment in line with strategic, tactical, and operational targets in the waste management system. In a study, Habagil and coworkers presented a practical approach for the utilization of "Organic Fraction of Municipal Solid Waste" at the WWTP in Varberg, Sweden (Habagil et al., 2020). The United Nation is focused on the greener WTE technologies for achieving the sustainable development objectives. Among different sectors, sustainable bio-economy, electricity, and waste management are the most dynamic areas. Ali et al. believed generation of electricity from WTE supply chain technologies have been controlled in scale with respect to the three-dimensional sustainability structure including social, environmental, and economic elements (Ali et al., 2020). However, many studies are discovering energy recovery from waste, as a feasible resort. Still, waste management is one of the most challenging issues in energy planning. Di Matteo and coworkers, defined sustainability as waste turning from a "problem" to a "renewable resource" (Di Matteo et al., 2017). Therefore, efficient use of municipal solid waste as a source of energy is one of the first steps towards low-carbon cities. Ohnishi et al. believed a network of multiple sectors that can produce and utilize energy from waste is needed to improve energy efficiency (Ohnishi et al., 2018). They reported this strategy has already been adopted at the urban scale in several developed countries as a way to enhance environmental efficiency and reduce negative impacts. In this case, an examination of the supply chain of wastes as a source of materials with potential to generate energy is necessary. This examination can improve the design of a practical WTE process that will create synergy and mutually beneficial relationship between industry and the waste management sector (Ohnishi et al., 2018). To achieving the CE principles, WTE seems to be a useful methodology due to resource regeneration, and must optimize resource and environmental sustainability within the closed-loop system in the supply chains. Vital resources could be optimized by minimizing waste, emissions, energy leakage, and resource input. Tseng and coworkers, expressed their concerns about multi-level supply chain system as a challenge for the CE community which needs more investigations (Tseng et al., 2020).

4. Energy recovery

The rising cost of fuel, supply water with low cost, and the effects of climate change and drought are putting a complex array of pressures on water, food, energy, and ecosystems. Increasing the use of renewable sources to generate energy, such as water for hydropower and biomass for bioenergy produce positive economic and mitigation benefits, but it can also negatively affect stressed water supplies (Zarei, 2020a, 2020b). Therefore, energy recovery from unconventional water resources such as wastewater resources seems to be an efficient and feasible plan. Also, Lee et al. offered a unique opportunity for reducing energy demand and it's associated environmental impacts by on-site energy recovery (e.g., biogas or waste heat) in the wastewater treatment systems (Lee et al., 2017). Wastewater is a crucial component of the water-energy nexus. Despite of requiring significant amounts of energy for collection and treatment of wastewater, it can be a main source of energy and it's limitless potential is indisputable (Meda et al., 2012). Sharif et al. reported almost 7%–8% of the world's total generated energy which is produced by fossil fuels and results in more GHGs emissions is used for drinking water production and distribution (Sharif et al., 2019). Energy recovery in the shape of biogas, biodiesel, hydrogen, electric power, and thermal energy can be done through heat pumps in WWTPs, mechanical, and thermal pretreatments technologies, and high temperature streams by heat exchanger (Bertanza et al., 2018). Three main opportunities for optimizing the water-energy use in a thermoelectric power plant cooling system were suggested by Pan et al.; (1) fit-for-purpose approach to improving energy efficiency, (2) advanced cooling technologies for enhancing water efficiency, and (3) implementations of green chemistry practices (Pan et al., 2018). The widespread application of available technologies is restrained by limited market opportunities and other obstacles related to user acceptance and economic aspects. Drechel et al. believed, energy recovery from wastewater has an impressive economic potential in terms of reducing energy use, operational costs and it's carbon footprint (Drechsel et al., 2015). So far, energy recovery at WWTPs plays a significant role as a sustainability driver for development plans and shaping better future.

4.1. Water-energy nexus

Currently various rules and laws control water, energy, and food resources due to their interconnected relationship. Recently the water-energy-food nexus approach is more accepted by different parties for unified commercial sectors to efficient implementation of the SDGs (Olawuyi, 2020). Water-Energy nexus thinking is important, because it supports various shapes of life on earth, and it's understanding can help to achieve the SDGs. "Clean water and sanitation" and "affordable and clean energy" are two of the 17 SDGs suggested by the United Nations in 2016 (Zarei, 2020a, 2020b). Water and energy are highly interdependent on each other. Water is used for power generation and energy can supply water by extraction, transmission, treatment, and distribution. Water and energy interdependencies clearly is observed in the recovery of energy and nutrients from wastewater. Therefore, the water-energy nexus concept was established but hardly take credit in many countries (Leivas et al., 2020). Brandoni and Bošnjaković believed, a CE framework could be key to motivate decision makers due to lack of recognition on the linkage between energy and water resources as one of the fundamental obstacles to achieving the nexus thinking (Brandoni and Bošnjaković, 2018). In this case, scholars and policymakers should seize new opportunities of energy recovery from wastewater and take actions to address the future global challenges.

4.2. Biogas and biodiesel

Anaerobic digestion process has been studied, developed, and highly recommended as environmentally friendly and cost-effective technology for biodegradable materials degradation, sludge stabilization, and biogas production from wastewater resources. Biogas production by chemical energy contained in organic matters from wastewater through the anaerobic digestion of biosolids for electric power and thermal energy generation is one of the most promising applications of on-site energy recovery. By sewage sludge transformation into biogas, a mixture of methane (50%–70%), carbon dioxide (30%–50%), and traces of other gases, such as nitrogen and hydrogen are produced (Shen et al., 2015). As one of the basic sources of energy in the WWTPs, produced methane in the treatment plant can be used to feed the gas engines and produce both electrical and thermal energy (Tyagi and Lo, 2013). Widespread sources such as organic fraction of municipal solid waste, waste activated sludge, animal manures, industrial wastes, energy crops, micro-algae, and macro-algae are used in the anaerobic digestion process (Rezaee et al., 2020). The optimization methods such as mechanical, thermal, chemical, biological, and combination of them can be adopted aiming to higher biodegradability of sludge. The four main phases of biochemical reactions; "hydrolysis, acidogenesis, acetogenesis, and methanogenesis" will transform organic substance of sewage sludge into biogas and the products of all the previous phases are converted into the methane and carbon dioxide as final products (Elalami et al., 2019). Rezaee et al. reviewed five hybrid pathways for anaerobic digestion including "biochar-amended anaerobic digestion, digestate-derived biochar and hydrochar, anaerobic digestion of aqueous phase liquid derived from pyrolysis, and gasification of digestate" (Rezaee et al., 2020). Zhen et al. reported the biogas produced in a digester via anaerobic digestion as the main energy source in WWTPs has a great energy potential (65% methane content). It was estimated that WWTPs with sludge digestion consume about 40% less net energy than WWTPs without anaerobic digestion (Zhen et al., 2017). Also, for improving anaerobic digestion process in WWTPs thermal hydrolysis technologies like Cambi, Biothelys, and Exelys are highly recommended and from economic and environmental point of view, co-digestion of sewage sludge with other biodegradable waste is developed (Hagos et al., 2017). Thus, for reducing the cost of municipal and industrial organic waste management co-digestion of organic waste in combination with sewage could be an economic option. Recovered heat and energy by co-digestion of sewage sludge in Mossberg WWTP (Germany) for 10 years as a real example is much higher than the internal demand of WWTP. Hagos et al. observed a 50% higher biogas production in a shorter hydraulic retention time in the first WWTP in Washington which applied Cambi technology (Hagos et al., 2017). Gherghel et al. highlighted calorific value of biogas as a beneficial characteristic for using in electricity generation, heat production, and as a fuel for vehicles among other uses (Gherghel et al., 2019). Due to complex structure and slowly biodegradable nature of biogas production from different waste resources still limitations retard the process (Atelge et al., 2020). From the CE point of view, anaerobic digestion process can be an appropriate solution due to significant energy production and preserving the general operating cost of the WWTP (Do et al., 2018). Therefore, anaerobic digestion as a bioenergy production process will only become economically practical if subsidies are made available to ensure it's competitiveness with commercial natural-gas supplies (Kleerebezem et al., 2015).

In the last decades, by population growth and increasing of demands for energy-based resources, biodiesel as a beneficial alternative, is received positive comments (Tyagi and Lo, 2013). Vegetable oils are the main resources for biodiesel production due to rare and expensive raw materials with the high production cost (Olkiewicz et al., 2016). In this case, sewage sludge with high lipid content and low cost which is mostly generated in WWTPs, can be an ideal candidate for biodiesel production (Di Maria et al., 2016). Transesterification technology is commonly used for this purpose (Jung et al., 2019). Choi et al. discussed about different lipidic composition of sewage sludge depending on the origin of the wastewater, and suggested it is essential to analyze the lipid content at every step and time to select the best treatment approaches that will work efficient in each case (Choi et al., 2019). Gharghel et al. recommended to choose microorganisms for the wastewater treatment in the WWTPs based on their application to generate more oil contents for more biodiesel production (Gherghel et al., 2019). Note that, for transesterification process catalysts play an essential role and in the other hand a high percentage of free fatty acids cause disorders owing to soap formation when common basic catalysts, such as sodium hydroxide, are used. In this case, acid catalysts are recommended despite of their disadvantage to slow down the reactions (Wu et al., 2016). Therefore, scientific associations and researchers try to find new material as catalyst that is suitable for situation like this or at least finding new non-catalyst process for production of biodiesel in a short time (Jung et al., 2019; Zhang et al., 2020a, 2020b).

4.3. Hydrogen

The demand for beneficial, sustainable, and renewable sources of energy such as hydrogen is increased due to GHGs emissions, rising prices, and major environmental problems of fossil fuels. Along with biogas and biodiesel, hydrogen can be credited as one of the most eco-friendly energy resources which is having high energy content. Biohydrogen production can be implemented by biological processing of waste materials like agricultural and industrial discharges (Sharma et al., 2020). Electrohydrolysis and biological treatments, such as microbial fermentation under dark or photo fermentation can be applied to produce hydrogen from wastewater (Preethi, 2019; Yarımtepe et al., 2019). Sharma et al. considered dark fermentation as the master of biological processes for the transformation of organic substrates to hydrogen (Sharma et al., 2020). Other processes such as ultraviolet radiation (as a pre-treatment process) and an ultrasonic pre-treatment by 80.6% and 120% increasing in the hydrogen content production was suggested (Elbeshbishy et al., 2010; Wang et al., 2010). Yang et al. proved addition of oxidizing agent, increased the efficiency of gasification and as a result improved the rate of hydrogen production (Yang et al., 2019). Despite the unique characteristics, some processes can produce only the hydrogen from wastewater. Sometimes drying pre-treatments processes notably increases the cost of this process and rate of energy input due to the high water content in the sludge (Zhu et al., 2018). Thus, Ibrahim and Akillli suggested using of catalyst as a key factor in reducing the activation energy of the reactions and for achieving optimal operating conditions which could also improve the efficiency of gasification by being hydrogen selective (Ibrahim and Akilli, 2019). Also, these processes are viable and cost-effectiveness which help to shift from linear to circular model of economy for sustainable development. Sharma et al. believed a productive action in the area of research and development of biological processes for hydrogen production technologies is required which improves the commercial capacity of biohydrogen production as an essential element of energy recovery for implementation of CE concept and sustainable development (Sharma et al., 2020).

4.4. Thermal energy

Heat pumps extract energy from different sources such as air, water, and earth. But, the effluents from WWTPs are promising and economical sources of heat for use in heat pumps (Culha et al., 2015). Although, the heat recovered from wastewater is discussed as low-quality heat. In this case, the system is called wastewater source heat pump (Hao et al., 2019). This heat are applicable for residential and commercial buildings, public spaces, industrial plants, water heating, sludge heating, heating/cooling, and infrastructures. The first heat pumps were built more than 20 years ago and recently heat pumps using wastewater are generally implemented in Europe, USA, Japan, South Korea, and China (Frijns et al., 2014). Also, more than 500 wastewater source heat pumps are applied around the world and the amount of energy that can be achieved by this approach is higher than achieved from chemical energy (Hepbasli et al., 2014). Hao et al. suggested the 3–5 kilo meters distance from the place where the recovered heat is used (Hao et al., 2019). Therefore, on-site consumption is one of the best options which can be used to heat digesters or even for sludge drying. Also, it can be applied outside to heat neighboring buildings (Đurđević et al., 2019). Recently, De Sanctis et al. evaluated the possibility of recovering thermal energy and water for agricultural purposes from sewage in a research study based on a sequencing batch biofilter granular reactor followed by sand filtration and coupled with a solar wastewater source heat pump (De Sanctis et al., 2020). Thermal energy storage facilities, such as aquifers could be a potential solution for mismatch between supply and demand in terms of time and location (Van der Hoek et al., 2016). Due to a reduced demand for district heating or cooling in spring and autumn, selling extra heat to neighboring consumers is a temporary option (Chae and Kang, 2013). As a successful and actual example, large-scale district heating and cooling systems using thermal energy derived from wastewater in Japan, can reduce energy consumption considerably. Energy savings in Osaka, achieved approximately 20–30% by introducing thermal energy recovery from effluents (Shareefdeen et al., 2016).

4.5. Electric power

Due to economic and environmental problems of using non-renewable energy resources, wastewater resources being embraced by on-site renewable electricity generations as a renewable energy resources (Strazzabosco et al., 2020). In the case of using on-site recovered electric power, the system can be beneficial especially when we have an energy up-rise prices. Along with biofuels and biogas production, electricity can be recovered and contaminated elements can be removed from wastewater resources by bioelectrochemical processes (Chen et al., 2019; Goenka et al., 2018; Gude, 2016; Tang et al., 2019). In this case, microbial fuel cell have considered as an applicable process for electric power recovery (Meena et al., 2019). But, for adoption in the large scale, this technology carries some challenges such as high price of the materials which applied to manufacture the electrodes, membranes, and poor efficiency in very low temperatures which reduce the metabolic rate of the microorganisms.

By hydropower stations installation, the hidden energy of wastewater can be recovered in it's path along with a WWTP. Based on seasonal, economic, infrastructural and demographic variations, the rate of flow, and the hydraulic head are counted as key parameters in hydropower design and WWTPs location. For achieving the optimal performance, hydropower designed based on a defined flow and pressure (Kehrein et al., 2020). Owing to the lower water flow available in a WWTP compared to rivers or waterfalls, the most practical systems would be mini and micro-hydropower (MHP) (Sari et al., 2018). Chacón et al. believed MHP is an applicable technology for irrigation networks to eliminate system overpressures and decrease the net energy consumption of the irrigation process on a small regional scale (Chacón et al., 2020). Hydropower as a renewable energy resource and eco-friendly option which generate non-stop energy throughout the year regardless of weather conditions, has many benefits that must be considered (Ak et al., 2017). But, suspended solids of wastewater resources can destruct mechanism of the system and it is relevant to the few number of WWTPs which have hydraulic power generators (Bousquet et al., 2017). Although, as a solution for this problem, Sarei et al. suggested to locate the power generation system at the exit of the plant, where the water is cleaner (Sari et al., 2018). Despite of lack a detailed analysis, economic viability of this approach is attributed to physical characteristics, present variations, and future market conditions together (Power et al., 2014). The overview of different technologies used for energy recovery (biogas, biodiesel, hydrogen, thermal energy, and electric power) from wastewater with their advantages and disadvantages are shown in Fig. 5.

4.6. Seizing the reuse opportunity

The United Nations-Water World Water Day theme in 2017 was "wastewater" which has aimed to raise awareness of this global problem and create opportunities among concerned organizations and institutions. The global population is estimated to rise to 8.5 billion people and the pressures will persuade countries to address the wastewater challenges and seize the reuse opportunity (Opec, 2018). The CE concept is capable to merging economic growth and sustainable development by consumption of reused resources, in response to the drawbacks of the conventional "take-make-consume-dispose" model of growth (Opec, 2018). In this case, eight pioneer cities as successful examples of cities which actually seize the opportunity of resources recovery with achieving benefits are discussed in Tables 2 and 3.

Governments in collaborate with private sector should take action lead to investing steadily in wastewater management and infrastructure to enable a transition to the CE concept, which bringing environmental, economic, and social benefits. Definitely the wide variety of examples incentivize development leaders, decision-makers, stakeholders, and researchers for more research and development to apply unified solutions for cities all around the world (Opec, 2018).

5. Circular economy for energy production by managing wastewater resources

Stahel considered the CE as a lake which reprocess the goods and materials, creates jobs, and saves energy while reducing resource consumption and waste. He believed "cleaning a glass bottle and using it again is faster and cheaper than recycling the glass or making a new bottle from minerals" (Stahel, 2016). From the comprehensive point of view, Geissdoerfer et al. defined the Circular Economy as "a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops (Geissdoerfer et al., 2017). This can be achieved through long-lasting design, maintenance, and repair, reuse, remanufacturing, refurbishing, and recycling" and they believed the concept has accepted by policymakers, influencing governments, and intergovernmental agencies at the local, regional, national, and international level (Geissdoerfer et al., 2017).

Climate change, rapid population growth, and mismanagement pose a major pressure on water as a scarce resource globally (Feingold et al., 2018; Koop and van Leeuwen, 2017; Walker et al., 2017). The rapid population growth add a heavy burden to societies for maintaining resource security as a vital element of sustainable and stable development. So, resources recovery from unconventional water resources can provide a commercially suc-

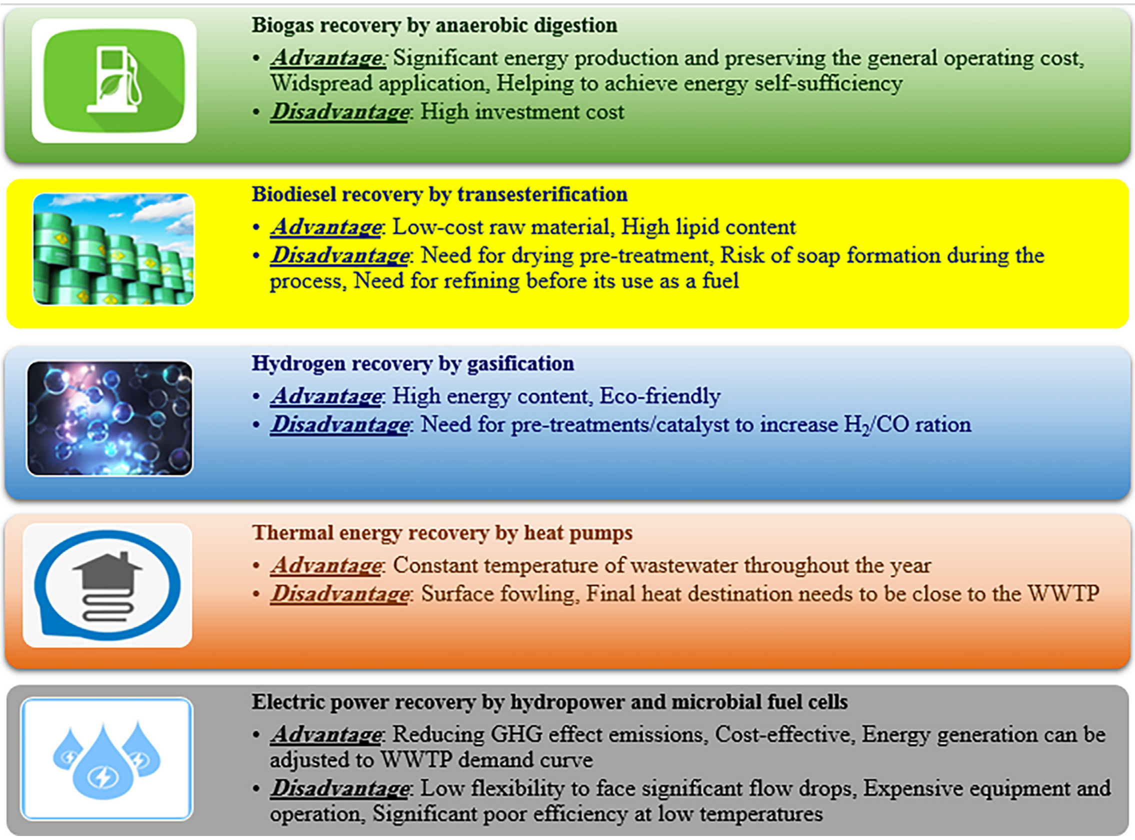

Fig. 5. The overview of different technologies used for energy recovery from wastewater with their advantages and disadvantages (Bousquet et al., 2017; Do et al., 2018; Gherghel et al., 2019; He et al., 2017; Lv et al., 2007; Olkiewicz et al., 2016; Sarpong and Gude, 2020; Shen et al., 2018; Tyagi and Lo, 2013).

Table 2
Statistical information about population, reuse wastewater resources, emissions, and energy recovery in the eight case studies till 2017 (Source: (Opec, 2018)).

	Aqaba	Bangkok	Beijing	Chennai	Durban	Kampala	Lima	Manila
Population	194,000	5.6 M	21.7 M	8.5 M	3.7 M	1.5 M	10 M	12.2 M
Wastewater/on-site sanitation (%)	10	60	5	-	84	60	17	85
Wastewater/sewer service coverage (%)	90	40	95	100	16	40	83	15
Wastewater treatment (L/d)	45 M (100%)	1.3B (100%)	4.4B (88%)	769 M (70%)	108 M (100%)	87 M (100%)	240 M (15%)	510 (100%)
Treated wastewater currently reused (%)	69	5	15	49	44	100	5	0
City-wide GHG emissions (ton CO^2e)	NA	NA	173 M	3.82 M	27.1 M	NA	15.4 M	29 M
Potential to reduce emissions from improved wastewater management (ton CO^2e/year)	−81,000	−638,000	−1044000 (−0.6%)	−235000 (−6.2%)	−438000 (−1.6%)	−114000	−652000 (−4.2%)	−1680000 (−5.8%)
Energy recovered (%)	100	62	45	77	8	227,000 KWh/y	Low	Low
Fertilizer recovered	No	Yes	Yes	No	Yes	Yes	No	Yes

cessful opportunity to reduce maintenance cost (Holmgren et al., 2016; Koop and van Leeuwen, 2017; Morée et al., 2013; UN Water, 2016). Wastewater management along with the CE as a unique occasion to reduce water consumption, can increase the living standards (McDonough and Braungart, 2010; Mo et al., 2009). Wastewater management is not only about water reuse but also is about beneficial resources recovery which is match with CE goals (Holmgren et al., 2016; Truffer et al., 2013; Walker et al., 2014). Contrary to linear economy, CE as a suitable framework tries to manage waste materials in an applicable way by engaging researchers, policymakers, economists, and policy leaders for sustainable and multidisciplinary development. From CE point of view, wastewater is a valuable and beneficial resource for recovering water, energy, and nutrients (Vu et al., 2020). In the case of wastewater resources management, CE approach can be a basic strategy for achieving the combined goals of sewage sludge disposal and energy recovery (Rosiek, 2020). But, Kočí et al. believed the demand for constant economic growth without accounting for environmental externalities is the fundamental challenge of CE concept (Kočí et al., 2016). Thus, by presenting by-product of one system for the other systems, integrated system is required more than ever (Baleta et al., 2019). Sfez and coworkers discussed how switching from a linear to a CE has consequences in the products assessment sustainability which are recovered from wastewater resources (Sfez et al., 2019). They wanted from producers, stakeholders, and policy makers as the game-changers to encourage the related sectors for the implementation of recovery technologies (Sfez et al., 2019). Also, the capacity of waste materials needs to be evaluated regard to the CE principles (Kasprzyk and Gajewska, 2019). Transition to CE will only be applicable by collab-

Table 3
Benefits of reuse wastewater resources in the eight case studies (Source: (Opec, 2018)).

Benefits	
Aqaba	- 4 Million US dollars in income from investment in infrastructure for wastewater treatment and reuse pays off in terms of tourism, public health and overall well-being of the residents. - Maintain the green areas and urban landscape, as well as cover the water demand of development projects and the industrial zone due to reuse of reclaimed water. - Reducing carbon emissions due to the resource recovery strategy through producing carbon neutral power from solar farms and biogas.
Bangkok	-Growing demand for both sewage collection. - Creating new markets and generating income from the collection of septic sludge and the sales of transformed sludge. - Due to on-site treatment pollution has been considerably reduced.
Beijing	- Full coverage of sewage treatment is possible in the six main urban districts in the short term. - Improving the water quality of the Liangshui River. - Approximately 47% of reused water is used for agricultural irrigation, 30% for environmental reuse and 20% for industrial reuse.
Chennai	- 15% of the city's water demand is provided through water recycling. Around 8% of the treated wastewater is sold to industries and up to 40.7% of domestic water needs in newly built houses are secured from in-situ wastewater reuse. - Improving operation of sewer networks. - Reducing the GHG emissions and electricity consumption by utilization of biogas for energy production. - New markets for wastewater treatment manufacturers and businesses were created.
Durban	- Recycling effluent has potable water by 7% and reduced the quantity of effluent directly discharged into the environment by 10%. - The use of recycled water for industries and agriculture in Durban has contributed to an additional 300,000 people being served with potable water. - Industrial users of recycled water pay 50% less than the cost of water from the conventional system.
Kampala	- Increasing income which is generated from sewerage services. - Improving the health and safety conditions for pit emptiers and utility workers through training. - Reducing the illegal dumping of fecal sludge. - Reducing the GHG emissions by utilization of biogas.
Lima	- Increasing ownership and responsibility towards reusing wastewater through building trust between all stakeholders. - Reuse of 3.5 m^3/s of treated wastewater to irrigate 3400 hectares of parks and gardens managed by Lima's Parks Service (SERPAR). - Creation a legal framework and enabling environment.
Manila	- Sector reform and privatization has led to strengthened partnerships among inter-governmental agencies and the private sector to accelerate sanitation coverage in Metro Manila. - A regulatory framework and legislation have paved the way to the development and implementation of plans that commit all stakeholders to 100% coverage and safely managed/reuse of wastewater and sludge by 2028. - Implementation of the polluter pays approach rather than issuing fines has been a key driver in incentivizing industries and residential compounds to install onsite/decentralized treatment systems. - Combined efforts from government agencies, private sector and residents has reduced pollutant loads to the environment and regenerated key resources that are key sources of drinking water and food.

oration among policy associations, scientific institutes, and financial cooperatives. Also, further efforts in research and technical processes should be made for resources recovery from wastewater and socio-economic transformation processes (Frenken, 2017a, 2017b; Hekkert et al., 2007; Kiparsky et al., 2013; Publishing, 2015; Smith and Stirling, 2010; Truffer et al., 2013).

5.1. Circular economy concept for energy recovery in the water and wastewater sector

Circular strategies should be considered for energy recovery from wastewater to minimize the negative environmental impacts of the industrial sectors (Micari et al., 2020). The CE concept is suitable for wastewater treatment sector like other industrial units. Recovery and recycle of waste materials guarantee the improvement of energy efficiency (Guerra-Rodríguez et al., 2020). Linear economy is not a good match for SDGs. Therefore, CE is recognized as a logical alternative due to multisectoral problems of resources scarcity and security. In this specific context, wastewater treatment sludge management is required for recovering beneficial raw materials and energy recovery (Kiselev et al., 2019). Smol et al. proposed a novel CE model framework as a systematic tool for an assessment of local or regional water and wastewater sector in the environmental management and planning, which includes the six following actions and presents possible ways of implement-

Fig. 6. Proposed CE model framework by Smol et al. in the water and wastewater sector.

ing CE principles in the water and wastewater sector, by considering environmental, technological, organizational, and societal changes (Fig. 6) (Smol et al., 2020). In addition to an extensive expertise about identity, physiology, ecology, and population dynamics of process-critical microorganisms, an efficient microbial biotechnology will improve recovery process stability and reduce GHGs emissions footprints in the CE framework (Nielsen, 2017). Finally, providing more relevant practices for resources and waste management, targeting all groups of materials and waste, designing long-term strategic plan, and cooperation of all parties could be helpful for transformation towards a CE concept (Lin et al., 2016).

5.2. Lessons learned, perspectives, and prospects

Environmental and economic benefits, are always originated from wastewater resources recovery (Cao et al., 2020). Implementation of a productive, economic, and practical wastewater treatment system is the very first step towards resources recovery from wastewater (Gu et al., 2017; Neczaj and Grosser, 2018). In this respect, influent concentration is one of the most critical parameters which has important impacts on technology selection by WWTPs and resource recovery processes. These high concentration influents usually needed the specific treatment processes to meet a strict effluent standard. Despite of high global warming potential as an obvious challenge of high concentration influents, advantages such as low energy consumption, low cost, and a high nutrient recovery potential can be really persuasive. Also, low concentration influents may not be beneficial for resource recovery due to their minimal capacities (Zhang et al., 2020a; Zhang et al., 2020b). Coupling the WWTPs with the energy generation stations for energy efficiency improvement can be reasonable and efficient for cleaner energy production. Note that, the implementation of these system integrations in absence of energy consumers in proximity of the WWTPs, and the temporal patterns of energy supply and energy demand could be questionable. For all the established facilities for wastewater reuse, there is a clear relationship among infrastructures, complex economic-environmental-social-political circumstances, and water-energy use limits. The most practical wastewater reuse plan for different regions of the world should be determined based on these factors and technological parameters (Hochstrat et al., 2007; Wilcox et al., 2016). In addition, cost-effectiveness is one of the biggest barriers for wastewater management projects. United States spend about 35% of energy budget of municipalities for water and wastewater treatment facilities and services (Chen et al., 2015). Chaudhary et al. highlighted the "best available technology" concept and the implementation of "decision support systems" as well as approaches based on "risk manage-

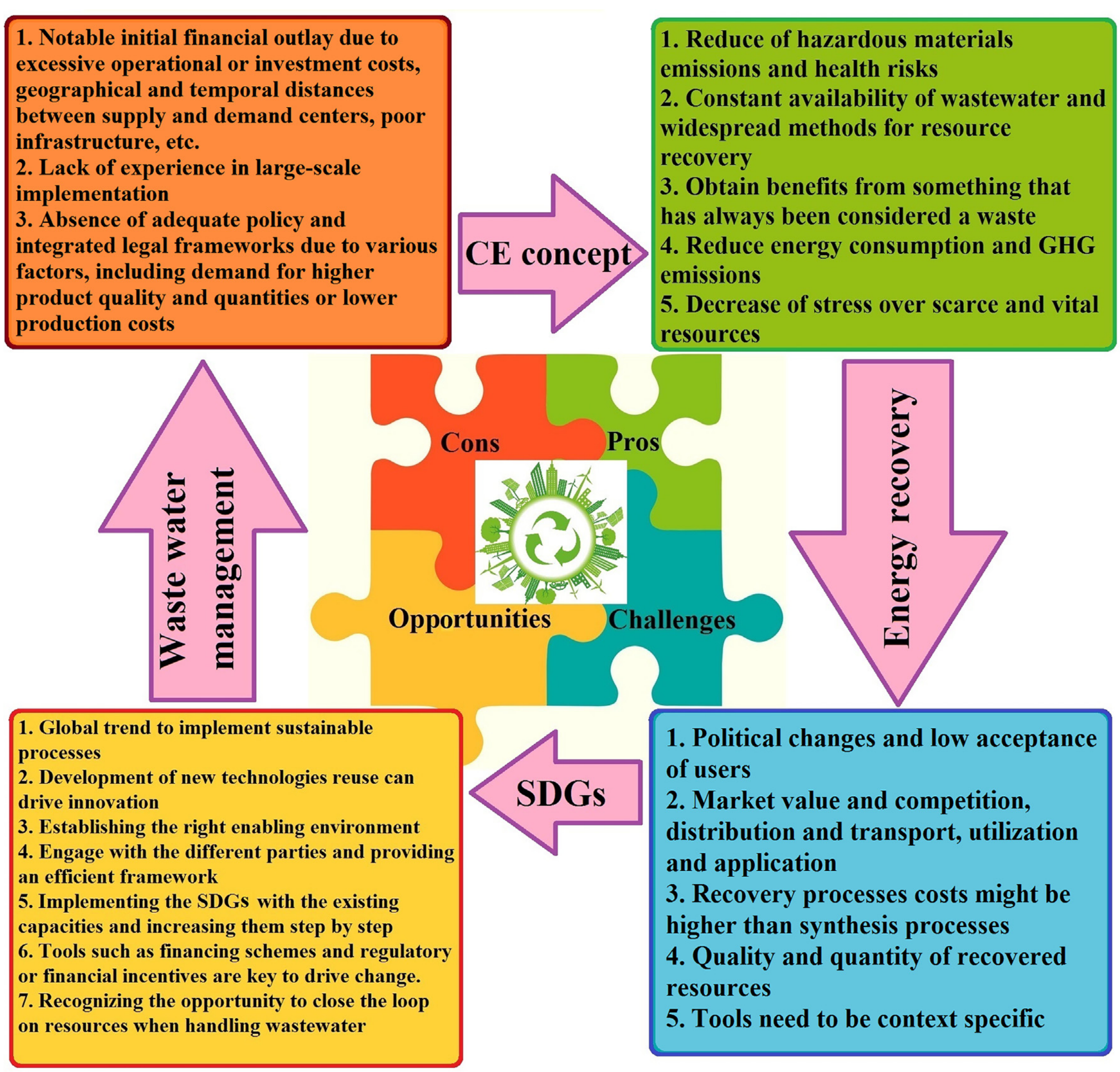

Fig. 7. The overview of lessons learned from pros and cons, challenges, and opportunities towards wastewater resources management for energy recovery from CE perspective.

ment" to consider wastewater reuse for multiple purposes (Chaudhary et al., 2019). Fig. 7 shows the overview of lessons learned from pros and cons, challenges, and opportunities towards wastewater resources management for energy recovery from CE perspective.

As a future prospective to overcome the challenges, a roadmap will be needed. In this case, the CE objectives in wastewater sector for energy recovery can be achieved through:

- Engaging the public support as an integral factor for implementing relevant projects;
- Establishing new policies which cover political, decisional, social, economic, and technological aspects for helping to achieve a fully CE in the wastewater and energy sector;
- Managing wastewater cycle by choosing the most applicable type of wastewater treatment system to overcome the risks and challenges and control the unpredictable circumstances;
- Enhancing knowledge and building capacity in order to develop international, national, and local action plans;
- Coordinating investments and financing in order to enhance the overall performance of wastewater management systems;
- Applying quality criteria to the end product, rather than to the input material, to promote market acceptance of high-quality materials from municipal wastewater and further stimulate the recycling of nutrients and other by-products of wastewater as a critical part of the CE;
- Shifting from wastewater treatment to water reuse and resource recovery by evaluating the potential wastewater reuse for cost recovery;
- Building resilient wastewater treatment infrastructures;
- Achieving all the benefits of wastewater management for energy recovery and reducing excessive costs, by applying integrated schemes which couple both wastewater treatment and reuse, rather than project-by-project approaches limited to a single sector.

6. Conclusions

Considering increasing demands and resources consumption, recovery of resources as a core of CE approach can offer a long-term strategy to better resources management and saving their security. Wastewater management as an inseparable piece of "sustainable future" puzzle, is a crucial element of the CE framework due to water and energy interdependencies and their part in shaping enabling environment by reducing stress over vital resources. For example, even energy self-sufficiency as a critical parameter for WWTPs can be achieved through biogas production and energy recovery from digesting supplementary feedstock in anaerobic co-digestion plans (Sarpong and Gude, 2020). This review explores the various advantages, opportunities, and challenges which are effective to implement CE in the wastewater sector for energy recovery. The application of this approach in the regions that are dealing with water scarcity is clear, but considering the beneficial impacts of energy recovery from wastewater, it can be useful in countries without resources issues, which are rare in number. The key findings are summarized as follows:

1- The 80% of world's wastewater is released into the environment without adequate treatment which is a valuable resource of clean water, energy, nutrients, and other resources can be recovered. At a time, when 36% of the world's population lives in water-scarce regions, wastewater treatment for reuse is part of the solution to water and energy scarcity and pollution problems.

2- Based on research and statistics, there is a synergy between country's level of industrial and municipal wastewater treatment and the income level. For example, the investment in infrastructure for wastewater treatment and reuse pays off in terms of tourism, public health and overall well-being of the residents and generates more than 4 Million US dollars in income for the Aqaba Water Company. High-income countries treated about 70% of the wastewater they generate, while the treatment percentage in upper middle-income countries, lower middle-income countries, and low-income countries are about 38%, 28%, and 8%, respectively. Specifically, the rate of municipal and industrial wastewater treatment in Europe, Middle East, and North Africa (MENA) region, and Latin American countries are estimated about 71%, 51%, and 20%, respectively. While, African countries are limited by poor financial resources for the developed wastewater management and 32 out of 48 Sub-Saharan African countries had no data available on wastewater generation and treatment (Sato et al., 2013). Also, more than 500 wastewater source heat pumps are applied around the world and the amount of energy that can be achieved by this approach is higher than achieved from chemical energy (Hepbasli et al., 2014).

3- With increase of energy consumption, water usage increases directly and this could enhance potential of conflict over vital resources, especially when resources are limited or shared. It should be noted that unlike energy, which can be obtained from multiple sources, water has no alternative origin. Therefore, wastewater reuse can be a key alternative source of fresh water in the CE concept. Future policymakers and stakeholders for the water-energy sectors should certainly consider the water-energy nexus at the regional, local, and worldwide level to achieve maximum environmental, social, political, and economic benefits for all parties.

Still, there is a huge capacity for development of the novel technological approaches for energy recovery from wastewater, which would enhance system performance and improve their efficiency. Therefore, we should change our perspective about wastewater, from worthless component to a fruitful resource with a major financial value. Note that, for energy recovery from wastewater in CE concept to become a reality, legal and institutional frameworks are needed. Also, governments and private institutes should dedicate their efforts to unify researchers, policymakers, stakeholders, and development leaders with different point of view for creating an integrated framework.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Ahmed, M., Ahmad, S., Tariq, M., Fatima, Z., Aslam, Z., Raza, M.A., Abbasi, N.A., 2020. Wastes to be the source of nutrients and energy to mitigate climate change and ensure future sustainability: options and strategies. J. Plant Nutr., 1–25

Ak, M., Kentel, E., Kucukali, S., 2017. A fuzzy logic tool to evaluate low-head hydropower technologies at the outlet of wastewater treatment plants. Renew. Sustain. Energy Rev. 68, 727–737.

Ali, J., Rasheed, T., Afreen, M., Anwar, M.T., Nawaz, Z., Anwar, H., Rizwan, K., 2020. Modalities for conversion of waste to energy — challenges and perspectives. Sci. Total Environ. 727. https://doi.org/10.1016/j.scitotenv.2020.138610.

Amann, A., Zoboli, O., Krampe, J., Rechberger, H., Zessner, M., Egle, L., 2018. Environmental impacts of phosphorus recovery from municipal wastewater. Resour. Conserv. Recycl. 130, 127–139.

Atelge, M.R., Atabani, A.E., Banu, J.R., Krisa, D., Kaya, M., Eskicioglu, C., Duman, F., 2020. A critical review of pretreatment technologies to enhance anaerobic digestion and energy recovery. Fuel 270. https://doi.org/10.1016/j.fuel.2020.117494.

Baleta, J., Mikulčić, H., Klemeš, J.J., Urbaniec, K., Duić, N., 2019. Integration of energy, water and environmental systems for a sustainable development. J. Cleaner Prod. 215, 1424–1436.
Batstone, D.J., Hülsen, T., Mehta, C.M., Keller, J., 2015. Platforms for energy and nutrient recovery from domestic wastewater: a review. Chemosphere 140, 2–11. https://doi.org/10.1016/j.chemosphere.2014.10.021.
Becerra-Castro, C., Lopes, A.R., Vaz-Moreira, I., Silva, E.F., Manaia, C.M., Nunes, O.C., 2015. Wastewater reuse in irrigation: a microbiological perspective on implications in soil fertility and human and environmental health. Environ. Int. 75, 117–135.
Bengtsson, S., Karlsson, A., Alexandersson, T., Quadri, L., Hjort, M., Johansson, P., Karabegovic, L., 2017. A process for polyhydroxyalkanoate (PHA) production from municipal wastewater treatment with biological carbon and nitrogen removal demonstrated at pilot-scale. New Biotechnol. 35, 42–53.
Bertanza, G., Canato, M., Laera, G., 2018. Towards energy self-sufficiency and integral material recovery in waste water treatment plants: assessment of upgrading options. J. Cleaner Prod. 170, 1206–1218.
Blomsma, F., Brennan, G., 2017. The emergence of circular economy: a new framing around prolonging resource productivity. J. Ind. Ecol. 21 (3), 603–614.
Bolognesi, S., Bernardi, G., Callegari, A., Dondi, D., Capodaglio, A.G., 2019. Biochar production from sewage sludge and microalgae mixtures: properties, sustainability and possible role in circular economy. Biomass Convers. Biorefin., 1–11
Bousquet, C., Samora, I., Manso, P., Rossi, L., Heller, P., Schleiss, A.J., 2017. Assessment of hydropower potential in wastewater systems and application to Switzerland. Renewable Energy 113, 64–73.
Brandoni, C., Bošnjaković, B., 2018. Energy, food and water nexus in the European Union: towards a circular economy. Proc. Instit. Civil Eng.-Energy 171 (3), 140–144.
Campbell-Johnston, K., Vermeulen, W.J., Reike, D., Bullot, S., 2020. The circular economy and cascading: towards a framework. Resour. Conserv. Recycl. X.
Cao, K., Zhi, R., Zhang, G., 2020. Photosynthetic bacteria wastewater treatment with the production of value-added products: a review. Bioresour. Technol. 299.
Chacón, M.C., Díaz, J.A.R., Morillo, J.G., McNabola, A., 2020. Estimating regional potential for micro-hydropower energy recovery in irrigation networks on a large geographical scale. Renewable Energy.
Chae, K.-J., Kang, J., 2013. Estimating the energy independence of a municipal wastewater treatment plant incorporating green energy resources. Energy Convers. Manage. 75, 664–672.
Chaudhary, J., Chadik, P.A., Osborne, T., 2019. Application of Reclaimed Water for Irrigation: A Review.
Chen, W., Lu, S., Pan, N., Wang, Y., Wu, L., 2015. Impact of reclaimed water irrigation on soil health in urban green areas. Chemosphere 119, 654–661.
Chen, Z., Zhang, S., Zhong, L., 2019. Simultaneous sulfide removal, nitrogen removal and electricity generation in a coupled microbial fuel cell system. Bioresour. Technol. 291.
Choi, O.K., Park, J.Y., Kim, J.-K., Lee, J.W., 2019. Bench-scale production of sewage sludge derived-biodiesel (SSD-BD) and upgrade of its quality. Renewable Energy 141, 914–921.
Culha, O., Gunerhan, H., Biyik, E., Ekren, O., Hepbasli, A., 2015. Heat exchanger applications in wastewater source heat pumps for buildings: a key review. Energy Build. 104, 215–232.
de Sadeleer, I., Brattebø, H., Callewaert, P., 2020. Waste prevention, energy recovery or recycling – directions for household food waste management in light of circular economy policy. Resour. Conserv. Recycl. 160. https://doi.org/10.1016/j.resconrec.2020.104908.
De Sanctis, M., Altieri, V.G., Piergrossi, V., Di Iaconi, C., 2020. Aerobic granular-based technology for water and energy recovery from municipal wastewater. New Biotechnol. 56, 71–78.
Desmidt, E., Ghyselbrecht, K., Zhang, Y., Pinoy, L., Van der Bruggen, B., Verstraete, W., Meesschaert, B., 2015. Global phosphorus scarcity and full-scale P-recovery techniques: a review. Crit. Rev. Environ. Sci. Technol. 45 (4), 336–384.
Di Maria, F., Micale, C., Contini, S., 2016. Energetic and environmental sustainability of the co-digestion of sludge with bio-waste in a life cycle perspective. Appl. Energy 171, 67–76.
Di Matteo, U., Nastasi, B., Albo, A., Astiaso Garcia, D., 2017. Energy contribution of OFMSW (Organic Fraction of Municipal Solid Waste) to energy-environmental sustainability in urban areas at small scale. Energies 10 (2), 229.
Do, M., Ngo, H., Guo, W., Liu, Y., Chang, S., Nguyen, D., Ni, B., 2018. Challenges in the application of microbial fuel cells to wastewater treatment and energy production: a mini review. Sci. Total Environ. 639, 910–920.
Drechsel, P., Qadir, M., & Wichelns, D. (2015). Wastewater Economic Asset in an Urbanizing World, Springer. doi: 10.1007/978-94-017-9545-6.
Đurđević, D., Balić, D., Franković, B., 2019. Wastewater heat utilization through heat pumps: the case study of City of Rijeka. J. Cleaner Prod. 231, 207–213.
EIA, U. (2013). International energy outlook 2013 with projections to 2040. Washington, US.
El-Shafai, S.A., El-Gohary, F.A., Nasr, F.A., Van Der Steen, N.P., Gijzen, H.J., 2007. Nutrient recovery from domestic wastewater using a UASB-duckweed ponds system. Bioresour. Technol. 98 (4), 798–807.
Elalami, D., Carrère, H., Monlau, F., Abdelouahdi, K., Oukarroum, A., Barakat, A., 2019. Pretreatment and co-digestion of wastewater sludge for biogas production: recent research advances and trends. Renew. Sustain. Energy Rev. 114.
Elbeshbishy, E., Hafez, H., Nakhla, G., 2010. Enhancement of biohydrogen producing using ultrasonication. Int. J. Hydrogen Energy 35 (12), 6184–6193.
Feingold, D., Koop, S., van Leeuwen, K., 2018. The city blueprint approach: urban water management and governance in cities in the US. Environ. Manage. 61 (1), 9–23.
Frenken, K., 2017. A complexity-theoretic perspective on innovation policy. Complexity, Innov. Policy 3 (1), 35–47.
Frenken, K. (2017b). Political economies and environmental futures for the sharing economy. Philos. Trans. R. Soc. A, 375(2095), 20160367.
Frijns, J., Monteiro, A., de Graaff, M., Carriço, N., Covas, D., Cabrera Marcet, E., et al., 2014. Intervention concepts for energy saving, recovery and generation from the urban water system.
Gao, H., Scherson, Y.D., Wells, G.F., 2014. Towards energy neutral wastewater treatment: methodology and state of the art. Environ. Sci. Processes Impacts 16 (6), 1223–1246.
Geissdoerfer, M., Savaget, P., Bocken, N.M., Hultink, E.J., 2017. The circular economy–a new sustainability paradigm?. J. Cleaner Prod. 143, 757–768.
Gherghel, A., Teodosiu, C., De Gisi, S., 2019. A review on wastewater sludge valorisation and its challenges in the context of circular economy. J. Cleaner Prod. 228, 244–263.
Goenka, R., Mukherji, S., Ghosh, P.C., 2018. Characterization of electrochemical behaviour of Escherichia coli MTCC 1610 in a microbial fuel cell. Bioresour. Technol. Rep. 3, 67–74.
Gu, Y., Li, Y., Li, X., Luo, P., Wang, H., Robinson, Z.P., Li, F., 2017. The feasibility and challenges of energy self-sufficient wastewater treatment plants. Appl. Energy 204, 1463–1475.
Gude, V.G., 2016. Wastewater treatment in microbial fuel cells–an overview. J. Cleaner Prod. 122, 287–307.
Guerra-Rodríguez, S., Oulego, P., Rodríguez, E., Singh, D.N., Rodríguez-Chueca, J., 2020. Towards the implementation of circular economy in the wastewater sector: challenges and opportunities. Water 12 (5), 1431.
Guo, C., Tan, Y., Yang, S., Qian, Y., 2018. Development of phenols recovery process with novel solvent methyl propyl ketone for extracting dihydric phenols from coal gasification wastewater. J. Cleaner Prod. 198, 1632–1640.
Habagil, M., Keucken, A., Sárvári Horváth, I., 2020. Biogas production from food residues—the role of trace metals and co-digestion with primary sludge. Environments 7 (6), 42.
Hagos, K., Zong, J., Li, D., Liu, C., Lu, X., 2017. Anaerobic co-digestion process for biogas production: progress, challenges and perspectives. Renew. Sustain. Energy Rev. 76, 1485–1496.
Hao, X., Li, J., van Loosdrecht, M.C., Jiang, H., Liu, R., 2019. Energy recovery from wastewater: heat over organics. Water Res. 161, 74–77.
He, L., Du, P., Chen, Y., Lu, H., Cheng, X., Chang, B., Wang, Z., 2017. Advances in microbial fuel cells for wastewater treatment. Renew. Sustain. Energy Rev. 71, 388–403.
Hekkert, M.P., Suurs, R.A., Negro, S.O., Kuhlmann, S., Smits, R.E., 2007. Functions of innovation systems: a new approach for analysing technological change. Technol. Forecast. Soc. Chang. 74 (4), 413–432.
Hepbasli, A., Biyik, E., Ekren, O., Gunerhan, H., Araz, M., 2014. A key review of wastewater source heat pump (WWSHP) systems. Energy Convers. Manage. 88, 700–722.
Hochstrat, R., Joksimovic, D., Wintgens, T., Melin, T., Savic, D., 2007. Economic considerations and decision support tool for wastewater reuse scheme planning. Water Sci. Technol. 56 (5), 175–182.
Holmgren, K., Li, H., Verstraete, W., Cornel, P., 2016. State of the Art compendium Report on Resource Recovery from Water. International Water Association, The Hague.
Ibrahim, A., Akilli, H., 2019. Supercritical water gasification of wastewater sludge for hydrogen production. Int. J. Hydrogen Energy 44 (21), 10328–10349.
Jodar-Abellan, A., López-Ortiz, M.I., Melgarejo-Moreno, J., 2019. Wastewater treatment and water reuse in Spain. Curr. Situat. Persp. Water 11 (8), 1551.
Johir, M., George, J., Vigneswaran, S., Kandasamy, J., Grasmick, A., 2011. Removal and recovery of nutrients by ion exchange from high rate membrane bio-reactor (MBR) effluent. Desalination 275 (1–3), 197–202.
Jung, J.-M., Oh, J.-I., Kim, J.-G., Kwon, H.-H., Park, Y.-K., Kwon, E.E., 2019. Valorization of sewage sludge via non-catalytic transesterification. Environ. Int. 131.
Kabbe, C., Remy, C., Kraus, F., 2015. Review of Promising Methods for Phosphorus Recovery and Recycling From Wastewater. International Fertiliser Society.
Kadam, J., Dhawal, P., Barve, S., Kakodkar, S., 2020. Green synthesis of silver nanoparticles using cauliflower waste and their multifaceted applications in photocatalytic degradation of methylene blue dye and Hg 2+ biosensing. SN Appl. Sci. 2 (4), 1–16.
Kasprzyk, M., Gajewska, M., 2019. Phosphorus removal by application of natural and semi-natural materials for possible recovery according to assumptions of circular economy and closed circuit of P. Sci. Total Environ. 650, 249–256.
Kehrein, P., van Loosdrecht, M., Osseweijer, P., Garfí, M., Dewulf, J., Posada, J., 2020. A critical review of resource recovery from municipal wastewater treatment plants–market supply potentials, technologies and bottlenecks. Environ. Sci. Water Res. Technol. 6 (4), 877–910.
Kiai, H., Raiti, J., El-Abbassi, A., Hafidi, A., 2018. Recovery of phenolic compounds from table olive processing wastewaters using cloud point extraction method. J. Environ. Chem. Eng. 6 (1), 1569–1575.
Kiparsky, M., Sedlak, D.L., Thompson Jr, B.H., Truffer, B., 2013. The innovation deficit in urban water: the need for an integrated perspective on institutions, organizations, and technology. Environ. Eng. Sci. 30 (8), 395–408.
Kiselev, A., Magaril, E., Magaril, R., Panepinto, D., Ravina, M., Zanetti, M.C., 2019. Towards circular economy: evaluation of sewage sludge biogas solutions. Resources 8 (2), 91.

Kleerebezem, R., Joosse, B., Rozendal, R., Van Loosdrecht, M.C., 2015. Anaerobic digestion without biogas? Rev. Environ. Sci. Bio/Technol. 14 (4), 787–801.
Kocatürk-Schumacher, N.P., Bruun, S., Zwart, K., Jensen, L.S., 2017. Nutrient recovery from the liquid fraction of digestate by clinoptilolite. Clean–Soil, Air Water 45 (6), 1500153.
Kočí, V., Rocha, J. L., & Zakuciová, K. (2016). The concept of circular economy applied to CCS, waste and wastewater treatment technologies.
Koop, S.H., van Leeuwen, C.J., 2017. The challenges of water, waste and climate change in cities. Environ. Dev. Sustain. 19 (2), 385–418.
Kurup, G.G., Adhikari, B., Zisu, B., 2019. Recovery of proteins and lipids from dairy wastewater using food grade sodium lignosulphonate. Water Resour. Ind. 22.
Lam, H.L., Ng, W.P.Q., Ng, R.T.L., Ng, E.H., Aziz, M.K.A., Ng, D.K.S., 2013. Green strategy for sustainable waste-to-energy supply chain. Energy 57, 4–16. https://doi.org/10.1016/j.energy.2013.01.032.
Lee, M., Keller, A.A., Chiang, P.-C., Den, W., Wang, H., Hou, C.-H., Yan, J., 2017. Water-energy nexus for urban water systems: a comparative review on energy intensity and environmental impacts in relation to global water risks. Appl. Energy 205, 589–601.
Leivas, R., Laso, J., Abejón, R., Margallo, M., Aldaco, R., 2020. Environmental assessment of food and beverage under a NEXUS Water-Energy-Climate approach: application to the spirit drinks. Sci. Total Environ. 137576.
Leyva-Díaz, J., Monteoliva-García, A., Martín-Pascual, J., Munio, M., García-Mesa, J., Poyatos, J., 2020. Moving bed biofilm reactor as an alternative wastewater treatment process for nutrient removal and recovery in the circular economy model. Bioresour. Technol. 299.
Li, X., Long, J., Hua, Y., Chen, Y., Kong, X., Zhang, C., 2019. Protein recovery and anti-nutritional factor removal from soybean wastewater by complexing with a high concentration of polysaccharides in a novel quick-shearing system. J. Food Eng. 241, 1–9.
Lin, Y., Guo, M., Shah, N., Stuckey, D.C., 2016. Economic and environmental evaluation of nitrogen removal and recovery methods from wastewater. Bioresour. Technol. 215, 227–238.
Lv, P., Yuan, Z., Wu, C., Ma, L., Chen, Y., Tsubaki, N., 2007. Bio-syngas production from biomass catalytic gasification. Energy Convers. Manage. 48 (4), 1132–1139.
Lyu, S., Chen, W., Zhang, W., Fan, Y., Jiao, W., 2016. Wastewater reclamation and reuse in China: opportunities and challenges. J. Environ. Sci. 39, 86–96.
Masi, F., Rizzo, A., Regelsberger, M., 2018. The role of constructed wetlands in a new circular economy, resource oriented, and ecosystem services paradigm. J. Environ. Manage. 216, 275–284.
Mateo-Sagasta, J., Raschid-Sally, L., Thebo, A., 2015. Global Wastewater and Sludge Production, Treatment and use Wastewater. Springer, pp. 15–38.
McDonough, W., Braungart, M., 2010. Cradle to Cradle: Remaking the Way we Make Things. North Point Press.
Meda, A., Lensch, D., Schaum, C., Cornel, P., Lazarova, V., Choo, K., 2012. Energy and water: relations and recovery potential. Water Energy Inter. Water Reuse, 21–35.
Meena, R.A.A., Kannah, R.Y., Sindhu, J., Ragavi, J., Kumar, G., Gunasekaran, M., Banu, J.R., 2019. Trends and resource recovery in biological wastewater treatment system. Bioresour. Technol. Rep. 7.
Melia, P.M., Cundy, A.B., Sohi, S.P., Hooda, P.S., Busquets, R., 2017. Trends in the recovery of phosphorus in bioavailable forms from wastewater. Chemosphere 186, 381–395.
Micari, M., Moser, M., Cipollina, A., Tamburini, A., Micale, G., Bertsch, V., 2020. Towards the implementation of circular economy in the water softening industry: a technical, economic and environmental analysis. J. Cleaner Prod. 255.
Mo, H., Wen, Z., Chen, J., 2009. China's recyclable resources recycling system and policy: a case study in Suzhou. Resour. Conserv. Recycl. 53 (7), 409–419.
Mohammadi, M., Harjunkoski, I., 2020. Performance analysis of waste-to-energy technologies for sustainable energy generation in integrated supply chains. Comput. Chem. Eng. 106905.
Morée, A., Beusen, A., Bouwman, A., Willems, W., 2013. Exploring global nitrogen and phosphorus flows in urban wastes during the twentieth century. Global Biogeochem. Cycles 27 (3), 836–846.
Neczaj, E., Grosser, A. (2018). Circular economy in wastewater treatment plant–challenges and barriers Multidisciplinary Digital Publishing Institute Proceedings (Vol. 2, pp. 614).
Nielsen, P.H., 2017. Microbial biotechnology and circular economy in wastewater treatment. Microb. Biotechnol. 10 (5), 1102–1105.
Ohnishi, S., Fujii, M., Ohata, M., Rokuta, I., Fujita, T., 2018. Efficient energy recovery through a combination of waste-to-energy systems for a low-carbon city. Resour. Conserv. Recycl. 128, 394–405. https://doi.org/10.1016/j.resconrec.2016.11.018.
Olawuyi, D., 2020. Sustainable development and the water-energy-food nexus: legal challenges and emerging solutions. Environ. Sci. Policy 103, 1–9.
Olkiewicz, M., Plechkova, N.V., Earle, M.J., Fabregat, A., Stüber, F., Fortuny, A., Bengoa, C., 2016. Biodiesel production from sewage sludge lipids catalysed by Brønsted acidic ionic liquids. Appl. Catal. B 181, 738–746.
Opec, F., 2018. Wastewater Report 2018: The Reuse Opportunity. IWA International Water Association.
Pan, S.-Y., Du, M.A., Huang, I.-T., Liu, I.-H., Chang, E., Chiang, P.-C., 2015. Strategies on implementation of waste-to-energy (WTE) supply chain for circular economy system: a review. J. Cleaner Prod. 108, 409–421.
Pan, S.-Y., Snyder, S.W., Packman, A.I., Lin, Y.J., Chiang, P.-C., 2018. Cooling water use in thermoelectric power generation and its associated challenges for addressing water-energy nexus. Water-Energy Nexus 1 (1), 26–41.
Pandey, P., Shinde, V.N., Deopurkar, R.L., Kale, S.P., Patil, S.A., Pant, D., 2016. Recent advances in the use of different substrates in microbial fuel cells toward wastewater treatment and simultaneous energy recovery. Appl. Energy 168, 706–723.
Power, C.M., McNabola, A., Coughlan, P., 2014. Development of an evaluation method for hydropower energy recovery in wastewater treatment plants: case studies in Ireland and the UK. Sustainable Energy Technol. Assess. 7, 166–177.
Preethi, Usman, T. M. M., Rajesh Banu, J., Gunasekaran, M., & Kumar, G. (2019). Biohydrogen production from industrial wastewater: An overview. Bioresour. Technol. Rep., 7, 100287. doi: https://doi.org/10.1016/j.biteb.2019.100287.
Publishing, O., 2015. Water and Cities Ensuring Sustainable Futures. OECD Publishing.
Rezaee, M., Gitipour, S., Sarrafzadeh, M.-H., 2020. Different pathways to integrate anaerobic digestion and thermochemical processes: moving toward the circular economy concept. Environ. Energy Econ. Res. 4 (1), 57–67.
Robles, Á., Aguado, D., Barat, R., Borrás, L., Bouzas, A., Giménez, J.B., Serralta, J., 2020. New frontiers from removal to recycling of nitrogen and phosphorus from wastewater in the Circular Economy. Bioresour. Technol. 300.
Rosiek, K., 2020. Directions and challenges in the management of municipal sewage sludge in Poland in the context of the circular economy. Sustainability 12 (9), 3686.
Sari, M.A., Badruzzaman, M., Cherchi, C., Swindle, M., Ajami, N., Jacangelo, J.G., 2018. Recent innovations and trends in in-conduit hydropower technologies and their applications in water distribution systems. J. Environ. Manage. 228, 416–428.
Sarpong, G., Gude, V.G., 2020. Near future energy self-sufficient wastewater treatment schemes. Int. J. Environ. Res.
Sato, T., Qadir, M., Yamamoto, S., Endo, T., Zahoor, A., 2013. Global, regional, and country level need for data on wastewater generation, treatment, and use. Agric. Water Manag. 130, 1–13.
Sfez, S., De Meester, S., Vlaeminck, S.E., Dewulf, J., 2019. Improving the resource footprint evaluation of products recovered from wastewater: a discussion on appropriate allocation in the context of circular economy. Resour. Conserv. Recycl. 148, 132–144.
Shahtalebi, A., Sarrafzadeh, M., & Montazer, R.M., 2011. Application of nanofiltration membrane in the separation of amoxicillin from pharmaceutical wastewater.
Shareefdeen, Z., Elkamel, A., Kandhro, S., 2016. Modern Water Reuse Technologies: Membrane Bioreactors Urban water reuse handbook. CRC Press, pp. 419–428.
Sharif, M.N., Haider, H., Farahat, A., Hewage, K., Sadiq, R., 2019. Water–energy nexus for water distribution systems: a literature review. Environ. Rev. 27 (4), 519–544.
Sharma, S., Basu, S., Shetti, N.P., Aminabhavi, T.M., 2020. Waste-to-energy nexus for circular economy and environmental protection: Recent trends in hydrogen energy. Sci. Total Environ. 713.
Shen, C., Lei, Z., Wang, Y., Zhang, C., Yao, Y., 2018. A review on the current research and application of wastewater source heat pumps in China. Therm. Sci. Eng. Progr. 6, 140–156.
Shen, Y., Linville, J.L., Urgun-Demirtas, M., Mintz, M.M., Snyder, S.W., 2015. An overview of biogas production and utilization at full-scale wastewater treatment plants (WWTPs) in the United States: challenges and opportunities towards energy-neutral WWTPs. Renew. Sustain. Energy Rev. 50, 346–362.
Shiklomanov, I., 1999. World water resources and their use: a joint SHI/UNESCO product. http://webworld.unesco.org/water/ihp/db/shiklomanov/index.shtml.
Smith, A., Stirling, A., 2010. The politics of social-ecological resilience and sustainable socio-technical transitions. Ecol. Soc. 15 (1).
Smol, M., Adam, C., Preisner, M., 2020. Circular economy model framework in the European water and wastewater sector. J. Mater. Cycles Waste Manage., 1–16
Smol, M., Kulczycka, J., Henclik, A., Gorazda, K., Wzorek, Z., 2015. The possible use of sewage sludge ash (SSA) in the construction industry as a way towards a circular economy. J. Cleaner Prod. 95, 45–54.
Somoza-Tornos, A., Rives-Jiménez, M., Espuña, A., Graells, M., 2019. A circular Economy Approach to the Design of a Water Network Targeting the Use of Regenerated Water Computer Aided Chemical Engineering. Elsevier, pp. 119–124. Vol. 47.
Spriet, J., McNabola, A., Neugebauer, G., Stoeglehner, G., Ertl, T., Kretschmer, F., 2020. Spatial and temporal considerations in the performance of wastewater heat recovery systems. J. Cleaner Prod. 247.
Stahel, W.R., 2016. The circular economy. Nature 531 (7595), 435–438.
Strazzabosco, A., Kenway, S.J., Lant, P.A., 2020. Quantification of renewable electricity generation in the Australian water industry. J. Cleaner Prod. 254. https://doi.org/10.1016/j.jclepro.2020.120119.
Tang, J., Zhang, C., Shi, X., Sun, J., Cunningham, J.A., 2019. Municipal wastewater treatment plants coupled with electrochemical, biological and bio-electrochemical technologies: Opportunities and challenge toward energy self-sufficiency. J. Environ. Manage. 234, 396–403.
Truffer, B., Binz, C., Gebauer, H., Störmer, E., 2013. Market Success of on-site Treatment: A Systemic Innovation Problem. IWA Publishing, London, UK, pp. 209–223.
Tseng, M.-L., Chiu, A.S.F., Liu, G., Jantaralolica, T., 2020. Circular economy enables sustainable consumption and production in multi-level supply chain system. Resour. Conserv. Recycl. 154. https://doi.org/10.1016/j.resconrec.2019.104601.
Tyagi, V.K., Lo, S.-L., 2013. Sludge: a waste or renewable source for energy and resources recovery?. Renew. Sustain. Energy Rev. 25, 708–728.

Van der Hoek, J.P., de Fooij, H., Struker, A., 2016. Wastewater as a resource: Strategies to recover resources from Amsterdam's wastewater. Resour. Conserv. Recycl. 113, 53–64.

van Leeuwen, K., de Vries, E., Koop, S., Roest, K., 2018. The energy & raw materials factory: Role and potential contribution to the circular economy of the Netherlands. Environ. Manage. 61 (5), 786–795.

Voulvoulis, N., 2018. Water reuse from a circular economy perspective and potential risks from an unregulated approach. Curr. Opin. Environ. Sci. Health 2, 32–45.

Vu, M.T., Vu, H.P., Nguyen, L.N., Semblante, G.U., Johir, M.A.H., Nghiem, L.D., 2020. A hybrid anaerobic and microalgal membrane reactor for energy and microalgal biomass production from wastewater. Environ. Technol. Innov. 100834.

Walker, R.V., Beck, M., Hall, J., Dawson, R., Heidrich, O., 2017. Identifying key technology and policy strategies for sustainable cities: a case study of London. Environ. Develop. 21, 1–18.

Walker, R.V., Beck, M.B., Hall, J.W., Dawson, R.J., Heidrich, O., 2014. The energy-water-food nexus: Strategic analysis of technologies for transforming the urban metabolism. J. Environ. Manage. 141, 104–115.

Wang, H., Fang, M., Fang, Z., Bu, H., 2010. Effects of sludge pretreatments and organic acids on hydrogen production by anaerobic fermentation. Bioresour. Technol. 101 (22), 8731–8735.

Wang, S., Wang, Y., Zang, S.Q., Lou, X.W., 2020. Hierarchical hollow heterostructures for photocatalytic CO2 reduction and water splitting. Small Methods 4 (1), 1900586.

Water, U., 2016. WWAP (United Nations World Water Assessment Programme) (2016) (pp. 1–148). Paris, France: The United Nations World Water Development Report.

Water, U., 2017. Waste Water: The Untapped Resources. Facts and Figure. The United Nations World Water Development Report.

Wilcox, J., Nasiri, F., Bell, S., Rahaman, M.S., 2016. Urban water reuse: a triple bottom line assessment framework and review. Sustainable Cities Soc. 27, 448–456.

Wu, X., Zhu, F., Qi, J., Zhao, L., 2016. Biodiesel production from sewage sludge by using alkali catalyst catalyze. Procedia Environ. Sci. 31, 26–30.

Yang, X., Tian, S., Kan, T., Zhu, Y., Xu, H., Strezov, V., Jiang, Y., 2019. Sorption-enhanced thermochemical conversion of sewage sludge to syngas with intensified carbon utilization. Appl. Energy 254.

Yangui, A., Abderrabba, M., 2018. Towards a high yield recovery of polyphenols from olive mill wastewater on activated carbon coated with milk proteins: Experimental design and antioxidant activity. Food Chem. 262, 102–109.

Yarımtepe, C.C., Türen, B., Oz, N.A., 2019. Hydrogen production from municipal wastewaters via electrohydrolysis process. Chemosphere 231, 168–172.

Zarei, M., 2020a. Sensitive visible light-driven photoelectrochemical aptasensor for detection of tetracycline using ZrO2/g-C3N4 nanocomposite. Sensors Int. 1. https://doi.org/10.1016/j.sintl.2020.100029.

Zarei, M., 2020b. The water-energy-food nexus: a holistic approach for resource security in Iran, Iraq, and Turkey. Water-Energy Nexus 3, 81–94. https://doi.org/10.1016/j.wen.2020.05.004.

Zarei, M., Aalaie, J., 2019. Profiling of nanoparticle–protein interactions by electrophoresis techniques. Anal. Bioanal. Chem. 411 (1), 79–96.

Zarei, M., Bahrami, J., Zarei, M., 2019. Zirconia nanoparticle-modified graphitic carbon nitride nanosheets for effective photocatalytic degradation of 4-nitrophenol in water. Appl. Water Sci. 9 (8), 175.

Zarei, M., Zarei, M., 2018. Self-propelled micro/nanomotors for sensing and environmental remediation. Small 14 (30), 1800912.

Zhang, Q., Hu, J., Lee, D.-J., Chang, Y., Lee, Y.-J., 2017. Sludge treatment: current research trends. Bioresour. Technol. 243, 1159–1172.

Zhang, R., Zhu, F., Dong, Y., Wu, X., Sun, Y., Zhang, D., Han, M., 2020a. Function promotion of SO42−/Al2O3–SnO2 catalyst for biodiesel production from sewage sludge. Renewable Energy 147, 275–283.

Zhang, Y., Zhang, C., Qiu, Y., Li, B., Pang, H., Xue, Y., Huang, X., 2020b. Wastewater treatment technology selection under various influent conditions and effluent standards based on life cycle assessment. Resour. Conserv. Recycl. 154.

Zhen, G., Lu, X., Kato, H., Zhao, Y., Li, Y.-Y., 2017. Overview of pretreatment strategies for enhancing sewage sludge disintegration and subsequent anaerobic digestion: current advances, full-scale application and future perspectives. Renew. Sustain. Energy Rev. 69, 559–577.

Zhou, Y., Ma, M., Gao, P., Xu, Q., Bi, J., Naren, T., 2019. Managing water resources from the energy-water nexus perspective under a changing climate: a case study of Jiangsu province, China. Energy Policy 126, 380–390.

Zhu, J., Yang, Y., Yang, L., Zhu, Y., 2018. High quality syngas produced from the co-pyrolysis of wet sewage sludge with sawdust. Int. J. Hydrogen Energy 43 (11), 5463–5472.