Development and demonstration of an eco-innovative system for sustainable treatment and reuse of municipal wastewater in small and medium size communities in the Mediterranean region

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Abstract Treated municipal wastewater is considered a valuable non-conventional water resource. However, a substantial number of wastewater treatment plants installed in the Mediterranean region have proven to be unsuccessful copies of systems operating in technologically advanced countries. In addition to high operating and maintenance cost, these systems are often unsuited to address the local challenges of wastewater treatment. Therefore, treated municipal water is commonly under-exploited throughout the region. To address these challenges, the AQUACYCLE project aims to develop an eco-innovative wastewater treatment process scheme, comprised of anaerobic digestion, constructed wetlands and a solar photocatalytic reactor, for cost-effective treatment of urban wastewater and maximum environmental benefits. This paper presents the distinct features of the novel process scheme and the characteristics of three such demonstration units to be installed in Tunisia, Lebanon and Spain to test and validate the efficiency and cost-effectiveness of the hybrid system.

Keywords: municipal wastewater, reclamation, anaerobic digestion, constructed wetlands, solar photocatalytic oxidation

1. Introduction

Reclaimed municipal wastewater is considered a valuable non-conventional water resource. Especially in water stressed regions of the Mediterranean, the use of non-conventional water resources to complement or replace the use of fresh water resources provides multiple benefits in supporting the local economy (e.g., affording water for irrigation), improving the living standards of societies, reducing the pressures on natural resources and addressing climate change challenges.

Unfortunately, a substantial number of wastewater treatment plants installed in the Mediterranean region, particularly in MENA countries, have proven unsuccessful copies of treatment system operating in the western world. Aside from their high operating and maintenance costs, these systems are often unsuited to address the local challenges of wastewater treatment. Therefore, treated municipal water is commonly under-exploited throughout the region.

To address these challenges, the AQUACYCLE project, funded by EU under the ENI CBC MED programme, is set to develop an eco-innovative wastewater treatment process scheme (with the acronym APOC) comprising anaerobic digestion (AD), constructed wetlands (CWs), and a solar process for the cost-effective treatment of urban wastewater, with minimal operating cost and maximum environmental benefits. Thus, the partners in AQUACYCLE aspires to change the paradigm of viewing wastewater as an unsafe effluent, to that of an abundant all-year-round resource that has multiple uses.

2. The APOC system

2.1 Design characteristics

The APOC system is considered an integrated system that treats wastewater, both black and grey water, mostly at community, or even larger, scale, particularly promising for decentralized treatment implementations. A general view of APOC plant layout is shown in Figure 1. The components of this layout are only indicative and can be modified by the plant designer, depending on the influent characteristics and the treatment objectives. Specifically, different types of AD reactors and CWs can be applied, whereas the post-treatment in the novel solar raceway pond reactor (RPR) is a distinctive feature of the APOC system.

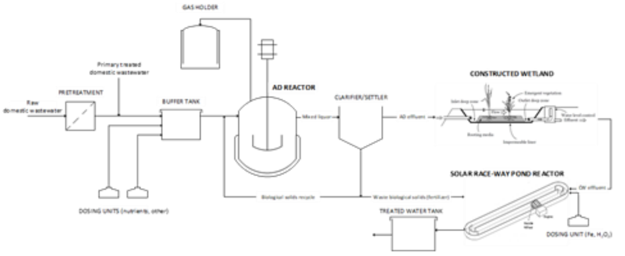

Figure 1. Flow diagram of a typical APOC system

Primary treatment: Since AD reactors are based on the propensity of anaerobic sludge (biomass) to aggregate into dense flocs or granules with good settling properties, it is crucial to prevent the solids to enter the anaerobic reactor, because they can hinder the subsequent anaerobic process, causing problems of blocking the pipes and mixing systems. Therefore, a good pretreatment of the raw wastewater is necessary to control the dry matter content of AD reactor (dry solids content of up to 7%). As minimum, a bar screen of 60 to 100 mm can be employed to remove large objects and sieves with minimum mesh size of 1 mm to 3 mm. Sand and oil are also problematic and should be removed from the feed.

Secondary treatment: The secondary treatment of the domestic wastewater is based on the anaerobic digestion process. The objective is to implement a sustainable process focusing on energy efficiency through biogas production as well as utilisation of the resulting nutrient-rich by-product (digestate). The capital investment costs, wastewater characteristics and methane production are the most important parameters, which will define the selection and the required size of the AD system (Huang et al. 2019). Several types of reactors are available in the market, with different systems of mixing and separation. The best known technologies for anaerobic treatment, that have been largely applied to domestic wastewater are the (i) Upflow Anaerobic Sludge Blanket (UASB), (ii) Anaerobic Baffled Reactor (ABR), (iii) Anaerobic Sequencing Batch Reactor (ASBR), (iv) Anaerobic Fluidized Bed Reactor (AFBR) and (v) the Anaerobic Filter (AF) reactor or Anaerobic Fixed Film Reactor (AFFR) (often referred to as Fixed Bed Reactor).

Tertiary treatment: Anaerobic treatment can reduce the organic matter of wastewater by a high percentage, but the quality of the effluent does not meet the requirements for discharge or reuse. In APOC, the *constructed wetland* (CW) is the chosen system to improve the quality of the anaerobic reactor effluent. CWs have been largely considered for water reuse, nutrient recovery and ecosystem services, as they can remove hazardous or recalcitrant substances, thus increasing the possible usages of the treated water while controlling the spread of harmful substances in the environment (Zhi and Ji 2012). Finally, they are "productive" themselves, as biomass is obtained by harvesting CW vegetation, which is further used as pelletized slow-releasing soil conditioner/fertilizer. CWs have additional environmental benefits, providing cooling through evapotranspiration, bird habitats, etc. There are various design configurations of CWs which can be classified according to the life form of the dominating macrophytes (free-floating, emergent, submerged), the flow pattern in the wetland systems (free water surface flow; subsurface flow: horizontal and vertical), the type of configurations of the wetland cells (hybrid systems, one-stage, multi-stage systems), the type of substrate (gravel, soil, sand, etc.) and the type of loading (continuous or intermittent loading). The selection of the particular CW configuration to be adapted in an APOC system depends on the AD effluent characteristics (nature and magnitude of the organic load) and the wastewater treatment needs.

Tertiary treatment: The post treatment of the CW effluent in a novel solar Raceway Pond Reactor consists of an interesting and feasible option for treating a substantial amount of wastewater by solar processes, such as photo-Fenton (SPF), solar/H_2O_2, solar/persulfate, etc. These are promising technologies for wastewater reuse applications due to their high disinfection potential and contaminants of emerging concern removal efficiency, associated with low reagents' consumption (e.g., iron complexing agents, H_2O_2) and different strategies to work at near-neutral pH. The most important parameters that play a relevant role in the optimization of RPRs are the liquid depth, residence time and reagents concentration, which could be changed according to the solar radiation availability. In this sense, the number of photons in the reactor may be adjusted to improve the kinetics and treatment capacity, depending on the season, the weather conditions (sunny or cloudy) and even geographic position.

According to specific water contamination, the APOC system can be appropriately designed to meet the required water quality standards, taking into account the potential constraints due to the levels of remaining residual charge. However, the reuse of treated wastewater needs particular attention, regarding health and safety, in accord with existing relevant standards (e.g., Regulation 2020/741/EU, NT 106-003/1989, FAO 2011).

2.2 APOC benefits

In comparison to conventional domestic wastewater treatment processes and other tertiary water reclamation methods (i.e., membrane processes, UV/O_3 disinfection, etc.) APOC is characterized by distinct attributes in relation to cost, social acceptability, simplicity of design, construction, operation and maintenance, hydrogeological conditions and local availability of materials and skills (Table 1). These attributes are related with the effective combination of processes which are less intensive, consume less energy, based on natural processes and result in products of significant added value (biogas, solid fertilizer and clean water for reuse).

In addition, the following APOC features need to be considered during the planning phase of such a resource recovery facility:

- ✓ The system can treat wastewater for both standard discharge and for reuse applications.
- ✓ The system is capable of treating domestic wastewater from secondary to tertiary level, and can be generally a community/committee-managed system.
- ✓ The system can be constructed according to feed-wastewater characteristics.
- ✓ Provides an effective solution for ecologically sensitive areas.
- ✓ APOC can be implemented using local skills and know-how to provide context-specific sanitation services and get optimum efficiency of the system.
- ✓ APOC can provide a renewable energy source. Depending on the demand, technical modifications can be made and biogas can be generated by the anaerobic digestion of the organic content to supply energy.
- ✓ APOC can provide a solid byproduct (anaerobic solid digestate) that can be used for land fertilization. APOC treated effluent can be used for urban, industrial, agricultural uses and groundwater recharge.

Table 1. Comparison between conventional domestic wastewater treatment systems and the APOC system

Feature	Conventional systems	APOC
Reliability	Require complex operation and maintenance schedules to ensure optimal performance	Does not require intensive maintenance for better performance
Environmental sustainability	Require higher amounts of energy and chemicals for their efficient operation	Reuse of reclaimed water and reduction of pressures on water resources; Reduction of CO_2 emissions by using a renewable energy source (solar energy) and natural processes (CWs); Low energy requirements
Financial sustainability	Substantial investment, (government subsidies) required for construction, operation and maintenance	Requires less capital cost when compared with centralized sewerage systems
Affordability	Scores low on affordability due to substantial cost of installation, sewerage network, operational and maintenance costs	Affordable due to lower costs when compared with centralized systems; Requires locally available materials

Although APOC requires more land than traditional intensive processes developed for large communities (e.g. activated sludge processes), the investment cost for the three components comprising the APOC system is generally lower, and the operating conditions are simpler, more flexible and allow more energy savings. Finally, the APOC system requires a smaller amount of manpower, little maintenance and less-specialised manpower than intensive techniques.

3. APOC system demonstration

With the aim to demonstrate the operation and promote the use of APOC, as an eco-innovative system of municipal wastewater treatment for non-conventional water supply and reuse, three APOC demo plants of 5-15 m^3/d of treatment capacity, will be established in selected sites in Spain, Tunisia and Lebanon (Figure 2). The construction of these systems is expected to be completed by the end of 2021 and thereafter the pilots' operation demonstration will follow.

3.1 Demo plant in Spain

The APOC demo plant will be installed in the premises of the Blanca wastewater treatment plant (WWTP), operated by ESAMUR, a partner of AQUACYCLE project. In this demo case, the effluent of the existing Upflow Anaerobic Sludge Blanket (UASB) reactor will feed, with flow rate 5 m^3/d, a system of two CWs, connected in series, one subsurface vertical wetland and one subsurface horizontal wetland. Due to vertical wetland intermittent flow needs, a buffer tank of 3 m^3 capacity will be installed, from which the AD liquid digestate will be pumped to the vertical wetland.

The effluent of the CWs will be finally led to a solar photoreactor in the form of a raceway pond (RPR) which consists of open channels through which the water is moved by a paddle wheel (Figure 1). The post-treatment of the CW effluent by the solar RPR aims to the effective disinfection and elimination of organic contaminants of emerging concern (i.e., pesticides, hormones, personal care products, drugs of abuse, etc.), contained in the MWWTPs effluents. The solar oxidation based processes involve chemical reactions that generate in situ highly reactive radical species, such as the hydroxyl radicals ($^{\bullet}OH$), which destroy most organic and organometallic pollutants until total mineralization (i.e., conversion into CO_2, water, and inorganic ions), thus leading to the inactivation of microorganisms, including enteric viruses, bacteria, spores and protozoa. Moreover, feeding small amounts of H_2O_2, and the addition of iron combined with natural sunlight, has been widely shown to be highly effective (Malato et al. 2009, De la Opra et al. 2017).

The design of the solar RPR will be similar for all three demo plants. It will be equipped with paddle wheel, reactive dosing pumps, pH, dissolved oxygen, temperature probes and UV sensor (Figure 3). RPR will be operated in batch and continuous mode (once optimal operating conditions have been obtained). It is noted that for a highly efficient disinfection process, it is desirable for the feed wastewater to the RPR to satify the following minimum requirements: NTU $\leq$ 5, Chemical Oxygen Demand < 100 mg/L, TSS (Total Suspended Solids) $\leq$ 10 mg/L.

3.2 Demo plant in Tunisia

This demo APOC plant will be connected to the Bent Saidane WWTP with the aim to improve the quality of the treated wastewater and to provide farmers in the region with a non-conventional water resource that can be used for un-restricted irrigation. The prime consideration for the design of the specific system will be a gravity-driven flow of the water between the different components/units of the APOC system. Based on the wastewater characteristics (COD 1000-1500 mgO_2/L, BOD 500-600 mgO_2/L, SS 400-500 mg/L, total nitrogen 70-200 mg/L, total phosphorous 1030 mg/L) and the treatment targets set (quality of treated wastewater for reuse in agriculture based on NT106.03 regulation), the design will include a high-rate anaerobic system (e.g., UASB), two sub-surface vertical flow CWs operating in parallel, two sub-surface horizontal flow CWs working in series, and finally a solar RPR similar to the one described above (Figure 3).

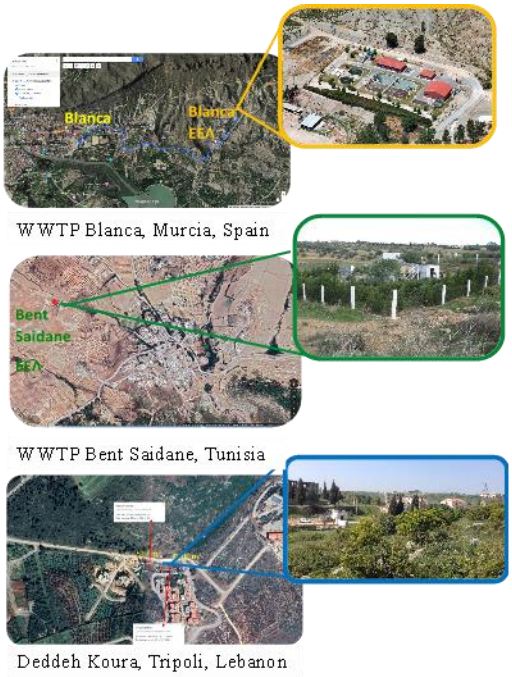

Figure 2. Photos of the areas of APOC demo plants installation in Spain, Tunisia and Lebanon.

3.3 Demo plant in Lebanon

The Lebanese APOC system will cover an area of around 300 m^2 and consist of: a) an intake structure to divert 5 m^3/d of domestic sewage from a residential community in Tripoli, b) screening, c) four-chamber Anaerobic Batch Reactor (ABR) made of reinforced concrete (area=16 m^2), d) an innovative horizontal flow aerated CW, using low area footprint with phragmites planted in gravel above a layer of geotextile and HDPE geomembrane (area=130 m^2), e) a solar RPR system for tertiary treatment disinfection (area=18 m^2), and f) on-line monitoring after each stage. The final effluent will be used to irrigate fruit or forest trees. All power will be supplied by solar panels to create a stand-alone system. The area surrounding the APOC will be secured by a fence. Surrounding retaining walls will be rehabilitated for securing safety of the system.

4. Evaluation of APOC performance

All APOC pilot systems will be demonstrated with real municipal effluents, in an operational environment, with the aim to:

- ✓ assess the effectiveness of the particular technology
- ✓ evaluate the operating performance of each system;
- ✓ determine the optimum operating parameters to be recommended for full-scale systems;
- ✓ identify/report problems, operation and maintenance issues and find solutions;
- ✓ evaluate the economic feasibility of APOC systems by performing a cost-benefit analysis, compared to conventional wastewater treatment systems.

Key performance indicators to be assessed during the operating demonstration of the three DEMO systems are related with (a) the treated effluent quality (removal of total faecal coliforms, biochemical and/or chemical oxygen demand, total suspended solids, potentially dangerous organisms), (b) energy savings and energy recovery (e.g., water treatment energy index), (c) treated effluent reuse potential (e.g., assessment of treated-water quality when compared to legal standards) and (d) overall cost-effectiveness of the novel process scheme (e.g., total annualized cost, operational expenditure). Other important attributes to be show-cased are the simplicity of design and construction based on local availability of materials and skills, operation and maintenance, and the adaptation to the different hydrogeological conditions.

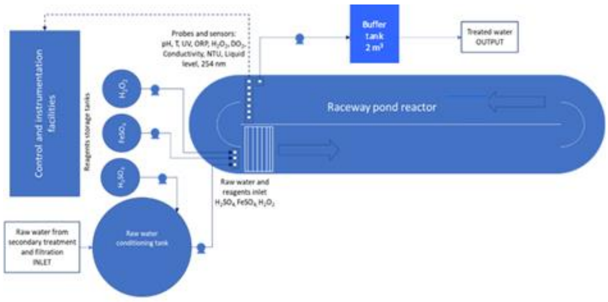

Figure 3. Process flow diagram of the solar RPR.

5. Acknowledgements

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