# Maximizing resource recovery from urban wastewater through an innovative facility layout

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**Abstract**
This research work proposes an innovative layout for urban wastewater treatment based on anaerobic technology, microalgal cultivation and membrane technology. The proposed Water Resource Recovery Facility (WRRF) system can treat urban wastewater efficiently, complying with legal discharge limits and allowing for resource recovery, i.e. energy, nutrients and reclaimed water. In addition, the proposed layout produces less solid wastes than a conventional wastewater treatment plant (WWTP) and it is possible to recover energy as biogas, not only from the original wastewater sources but also from the biomass generated in the WRRF system.

**Keywords**
Anaerobic membrane bioreactor (AnMBR); anaerobic co-digestion (AcoD); biogas; membrane photobioreactor (MPBR); resource recovery; urban wastewater.

## INTRODUCTION

This research work aims at demonstrating the potential of an innovative Water Resource Recovery Facility (WRRF) layout for urban wastewater treatment as an alternative to traditional aerobic urban wastewater treatment. The layout, based on anaerobic technology, allows for organic matter removal with a significant decrease in energy demands due to i) the absence of aeration needs and ii) the production of biogas. At the same time, sludge production is significantly reduced compared to aerobic processes. Microalgal autotrophic metabolism is used for nutrient removal from the wastewater line, whereas membrane filtration technology enhances the performance of all involved processes enabling the decoupling of solids retention time (SRT) and hydraulic retention time (HRT) in all the systems included. Additionally, membrane filtration also contributes to a solids-free final effluent that is susceptible of reclamation for different purposes (e.g., urban uses, irrigation, aquifer recharge, etc.). Nutrients are recovered and recycled through the solid and liquid fractions of the generated sludge. Hence, the layout can represent a paradigm shift transforming wastewater into a source of energy and valuable nutrients whilst producing a resource of water susceptible of reclamation (McCarty et al. 2011, Pretel et al. 2016)

The proposed layout consists of: an anaerobic membrane bioreactor (AnMBR) treating settled urban wastewater; a membrane photobioreactor (MPBR) that follows the AnMBR, where microalgal growth removes excess nutrients from the wastewater and where reclaimed water is produced; and a membrane-coupled anaerobic co-digester (M-AcoD) where primary sludge, AnMBR sludge and microalgal biomass are digested for enhanced biogas production.

This study aims at assessing the suitability of the above combination of innovative processes for urban wastewater treatment and resource recovery.

## MATERIAL AND METHODS

### Water Resource Recovery Facility (WRRF) layout description

The pilot scale WRRF was installed outdoors in the full-scale “Conca del Carraixet” wastewater treatment plant (WWTP) (Valencia, Spain) and is fed with the effluent from the primary settler. The layout of the WRRF is shown in Figure 1, where the sampling points are numbered. The WRRF is composed of three independent but connected treatment units: i) the AnMBR pilot plant, which carries out the biological wastewater treatment; ii) the MPBR pilot plant, for tertiary wastewater treatment (microalgal cultivation for nutrients recovery); and iii) the M-AcoD, where anaerobic co-digestion of primary sludge, AnMBR digestate and harvested microalgae is performed.

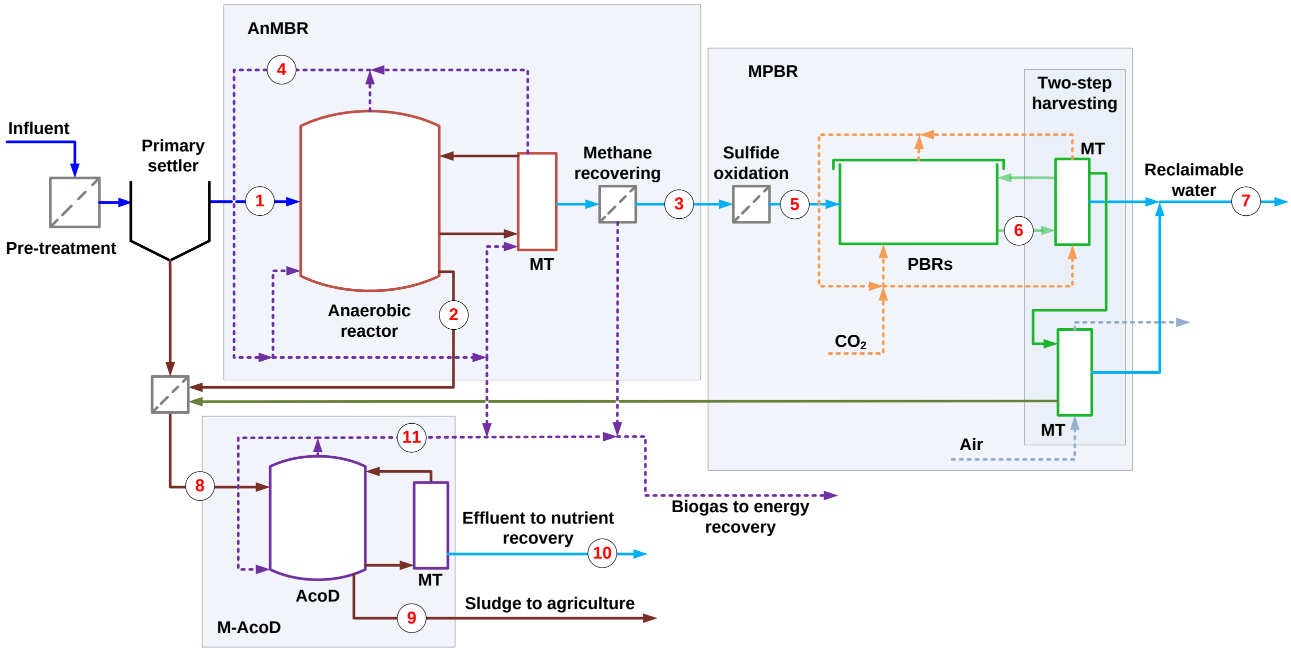

**Figure 1**. Layout of the WRRF including the sampling points (1-11).

The AnMBR plant mainly consists of an anaerobic reactor with a total volume of 1300 L (900 L working volume) connected to two membrane tanks (MT) each one with a total volume of 800 L (200 L working volume). Each MT is equipped with one industrial-scale hollow-fiber ultrafiltration membrane unit (PURON® KMS PUR-PSH31, 0.03-µm pores, 31-$m^2$ filtration area). The plant is operated with the sulfate-rich effluent from the primary settler of the full-scale WWTP. Biogas-assisted membrane-scouring is used to minimize cake layer formation by recycling a fraction of the biogas into the bottom of each MT.

The MPBR plant mainly consists of two 1.2-m height, 2-m width and 0.1-m depth methacrylate flat-plate photobioreactors (PBRs) with a working volume of 220 L. The PBRs are continuously stirred by gas sparging, which enables proper culture mixing and avoids wall fouling. The pH is controlled at 7.5 by pure $CO_2$ addition into the aeration system to avoid undesirable chemical processes such as phosphate precipitation and free ammonia stripping. The PBRs are connected to a two-step harvesting system (see e.g., Bilad et al. 2014) composed of two filtration units each one consisting in two MTs of 19 L. Each MT includes one membrane bundle (3.44 $m^2$ filtration area) that was obtained from one industrial-scale hollow-fiber ultrafiltration membrane unit (PURON® KMS PUR-PSH31, 0.03-µm pores). A fraction of the headspace gas is recycled to each MT to minimize cake layer formation. The MPBR plant is fed with the nutrient-rich effluent from the AnMBR plant.

The M-AcoD plant mainly consists of an anaerobic co-digester with a total volume of 1000 L (up to 900 L working volume) and a 1-L MT fitted with a 0.42-$m^2$ hollow-fiber ultrafiltration membrane unit (PURON® KMS). Primary sludge, AnMBR digestate and harvested microalgae are mixed in a 125-L equalization tank with a respective contribution of around 15%, 30% and 55%. To improve the mixing conditions in the co-digester and to favor the stripping of the produced gases from the liquid phase, a fraction of the produced biogas is recycled to the digester with a blower.

Table 1 displays the operating conditions of the pilot plants that conform the proposed WRRF layout.

**Table 1**. Operating conditions for the AnMBR, MPBR and M-AcoD plants. SRT: Sludge retention time; HRT: hydraulic retention time; PAR: photoactive Radiation; OLR: organic loading rate

| | **SRT** (d) | **HRT** (d) | **Temperature** (°C) | **Working volume** (L) | **Light PAR** ($\mu mol \cdot m^{-2} s^{-1}$) | **OLR** ($g\ COD \cdot L^{-1} \cdot d^{-1}$) |
|---|---|---|---|---|---|---|
| **AnMBR** | 68.2 ± 3.7 | 1.6 ± 0.1 | 20.3 ± 0.5 | 2100 | - | 0.15 ± 0.03 |
| **MPBR** | 4.3 ± 0.3 | 1.5 ±0.1 | 23.8 ± 1.1 | 440 | 273 ± 118 | - |
| **M-AcoD** | 69.7 ± 0.3 | 30.0 ± 0.3 | 55.0 ± 0.9 | 500 | - | 0.56 ± 0.04 |

## RESULTS AND DISCUSSION

Table 2 shows the average values and standard deviations of the main parameters analyzed in the water and sludge lines in the WRRF. As this table shows, the AnMBR effluent featured negligible suspended solids concentrations and low COD, accounting for a COD removal efficiency of 94%. From it, 55% was biologically degraded and only 8% ended up as methane, yielding 0.052 L $CH_4 \cdot g^{-1}$ COD and a biogas with a modest methane content of 15%. This low methane yield was attributed to sulfate reducers outcompeting methanogens, which resulted in the reduction of 57% of the influent sulfate to sulfide. Dissimilative sulfate reduction to sulfide was not complete due to the scarce biodegradability of the influent COD. The remaining COD was retained and removed from the system with the waste sludge, that accounted for 0.22 kg $VSS \cdot kg^{-1}$ COD. N and P content in water increased in the AnMBR due to the mineralization of N- and P-containing compounds, making it suitable for microalgal growth.

The MPBR plant was operated at solar irradiances and temperatures that varied according to the environmental conditions (see Table 1). A biomass productivity of 173 mg $VSS \cdot L^{-1} \cdot d^{-1}$ was achieved, together with a nitrogen removal efficiency of 84% (removal rate of 23.5 mg $N \cdot L^{-1} \cdot d^{-1}$) and a phosphorus removal efficiency of 89% (removal rate of 2.2 mg $PO_4\text{-}P \cdot L^{-1} \cdot d^{-1}$).

The M-AcoD yielded 0.19 L $CH_4 \cdot g^{-1}$ COD. Moreover, a nutrient-rich sludge and permeate was obtained. As Table 2 shows, 507 $mg \cdot L^{-1}$ of soluble nitrogen and 18 $mgP \cdot L^{-1}$ of $PO_4^{3-}$ were release from algae and sludge co-digestion. Thus, bio-nutrients could be recovered as commercial products such as struvite, ammonium sulfate and amendments.

The performance of the whole system revealed the potential of the proposed WRRF to achieve high methane-rich biogas productions: around 426 $L_{CH4}$ per kg of COD entering the WRRF (before primary settling), value higher than the stoichiometric one thanks to $CO_2$ uptake for microalgal growth. Moreover, the WRRF effluent met the legal discharge requirements according to the European Union Council Directive 91/271/EEC since average TN, TP and COD resulted in 7.9 mg $N \cdot L^{-1}$, 0.5 mg $P \cdot L^{-1}$ and 98 mg $COD \cdot L^{-1}$, respectively. Hence, this scheme represents an interesting alternative to shift from current WWTPs to the greener, new approach of WRRFs.

**Table 2**. Average and standard deviations of pH, Oxidation Redox Potential (ORP), Chemical Oxygen Demand (COD), Soluble COD (SCOD), Total Solids (TS), Volatile Solids (VS), Total Suspended Solids (TSS), Volatile Suspended Solids (VSS), Volatile Fatty Acids (VFA), Alkalinity (Alk), $CH_4$, and TN, SN, TP, $PO_4$-P, $S^{2-}$ and $SO_4$ concentrations in the sampling points of the proposed WRRF (See Figure 1). n.a.: not available.

| **Sampling point** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **pH** | 7.9 ± 0.2 | 7.4 ± 0.1 | n.a. | n.a. | n.a | 7.4 ± 0.2 | 7.4 ± 0.2 | n.a. | 7.5 ± 0.1 | n.a. | n.a. |
| **ORP (mV)** | n.a | -470 ± 18 | n.a | n.a | n.a | n.a | n.a | n.a | -522 ± 12 | n.a | n.a |
| **COD (mg COD·$L^{-1}$)** | 244 ± 36 | 4501 ± 101 | n.a | n.a | n.a | n.a | n.a | 16737 ± 1252 | 18626 ± 401 | n.a | n.a |
| **SCOD (mgCOD·$L^{-1}$)** | 98 ± 7 | n.a | 144 ± 11 | n.a | 81 ± 14 | n.a | 98 ± 10 | 1597 ± 283 | n.a | 1169 ± 64 | n.a |
| **TS (mgTS·$L^{-1}$)** | n.a | 4221 ± 214 | n.a | n.a | n.a | n.a | n.a | 11872 ± 1048 | 14013 ± 929 | n.a | n.a |
| **VS (%)** | n.a | 58.1± 0.8 | n.a | n.a | n.a | n.a | n.a | 73.5 ± 4.3 | 67.7 ± 2.3 | n.a | n.a |
| **TSS (mgTSS·$L^{-1}$)** | 83 ± 8 | n.a | n.a | n.a | n.a | 840 ± 69 | n.a | 9797 ± 1005 | 12322 ± 202 | n.a | n.a |
| **VSS (%)** | 80.7± 5.7 | n.a | n.a | n.a | n.a | 93.8 ± 2.2 | n.a | 75.8 ± 7.1 | 69.6 ± 1.3 | n.a | n.a |
| **VFA (mgHAc·$L^{-1}$)** | 1.9 ± 0.1 | n.a | 0.6 ± 0.1 | n.a | n.a | n.a | n.a | 755.7 ± 171.3 | n.a | 522.8 ± 35.3 | n.a |
| **Alk (mg$CaCO_3$·$L^{-1}$)** | 469 ± 50 | n.a | 523± 35 | n.a | n.a | n.a | n.a | 417 ± 121 | n.a | 1906.4 ± 67 | n.a |
| **$CH_4$ (%)** | n.a | n.a | n.a | 15 ± 3 | n.a | n.a | n.a | n.a | n.a | n.a | 62 ± 5 |
| **TN (mgN·$L^{-1}$)** | n.a | n.a | n.a | n.a | n.a | 83 ± 8 | n.a | 547 ± 105 | 650 ± 77 | n.a | n.a |
| **SN (mgN·$L^{-1}$)** | 41.0 ± 4.8 | n.a | 44.9 ± 5.8 | n.a | 44.8 ± 5.3 | n.a | 7.9 ± 1.2 | 154.2 ± 44.9 | n.a | 507.5 ± 19.8 | n.a |
| **TP (mgP·$L^{-1}$)** | n.a | n.a | n.a | n.a | n.a | 7.1 ± 1.1 | n.a | 145.9 ± 18.9 | 121.0 ± 7.2 | n.a | n.a |
| **$PO_4$-P (mgP·$L^{-1}$)** | 3.3 ± 1.2 | n.a | 3.9 ± 0.5 | n.a | 3.8 ± 1.1 | n.a | 0.5 ± 0.1 | 37.3 ± 8.8 | n.a | 17.7 ± 1.4 | n.a |
| **$S^{2-}$ (mgS·$L^{-1}$)** | n.a | n.a | 52.3 ± 4.8 | n.a | n.a | n.a | n.a | n.a | n.a | 33.4 ± 1.7 | n.a |
| **$SO_4$ (mg$SO_4$·$L^{-1}$)** | 305.6± 45.5 | n.a | 132.7± 31.1 | n.a | n.a | n.a | n.a | 129.3 ± 32.4 | n.a | n.a | n.a |

## CONCLUSIONS

The proposed WRRF layout enables efficient urban wastewater treatment whilst meeting legal discharge limits. In addition, less solid wastes are produced than in conventional WWTPs. Moreover, the proposed layout enables to recover energy in the form of biogas, not only from the original wastewater source but also from the biomass generated in the WRRF system.

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