Water reuse from wastewater: comparison between membrane bioreactor and ultrafiltration process

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Abstract: This study compares two different pilot plant configurations treating real wastewater to produce water for agricultural irrigation scope. The two configurations (Configuration I and II) operating in parallel have the same biological treatment unit. Specifically, the biological treatment occurs in an Integrated Fixed Film Activated Sludge – Intermittent Aeration (IFAS-IA) reactor. For Configuration I, the solid/liquid separation occurs through a membrane bioreactor (MBR). While, for configuration II a settler is devoted to the solid/liquid separation, followed by a tertiary ultrafiltration unit. During the plant operation, monitoring of the treatment performance coupled with the permeate quality according to the EU 741/2020 regulation was performed. Further, the nitrous oxide (N_2O) emission has been measured, and the carbon footprint and the reclaimed water quality index ($RWQI_1$) have been quantified. Results showed that Configuration I provided the best results in terms of both RWQI1 and carbon footprint. In terms of RWQ_1, Configuration I provided 0.62 kg pollutant/year, while Configuration II was 0.43 kg pollutant/year. Regarding carbon footprint, the lowest value (0.38 gCO_{2eq}/m^3) was obtained from Configuration II due to the reduced membrane fouling.

Keywords: wastewater; nutrient removal; membrane fouling; biofilm, sewage sludge production

1. INTRODUCTION

Water demand by the year 2030 is projected to be 64% higher than the current global water availability (Ahmad et al., 2022). This water is mainly used by the agricultural sector (around 70%) of global water consumption (FAO, 2021). Therefore, adopting alternative water sources concerning the natural ones is imperative. One approach for reducing the amount of natural water for irrigation is the adoption of treated wastewater (Chen et al., 2021). With this regard, wastewater treatment plants (WWTPs) are now transitioning into resource recovery facilities, extracting water, energy, nutrients (phosphorus and nitrogen), and biosolids. In view of being reused for agriculture scope, treated wastewater requires further treatment. The quality of reclaimed water for agricultural use varies depending on its intended purpose, leading the European Parliament to establish minimum water quality criteria (Regulation 2020/741) and classify reclaimed water into four classes. Regardless of the class, secondary treatment and disinfection are mandatory. The treatment degree decreases from the highest class (class A), which has no usage restrictions, to the lowest (class D), which is limited to commercially processed crops with no contact with humans or livestock. Concerns for irrigation water include suspended solids, organic matter, and pathogens (Fito and van Hulle, 2021). To be classified as class A, reclaimed water must meet specific criteria, including BOD_5 and TSS concentrations below 10 mg/L, turbidity below 5 NTU, and an E. coli count below 10 cfu/100 mL. Achieving this requires tertiary treatment following secondary treatment of wastewater are required. Over the years, several attempts have been made to combine WWTPs with systems able to remove both pollutants and pathogenic microorganisms. The adoption of ultrafiltration as a membrane bioreactor (MBR) and tertiary treatment has spread during the last decade. Ultrafiltration membranes allow high effluent quality standards; solid-free effluent is produced and substantially disinfected. However, adopting UF membrane filtration, both as MBR and tertiary treatment, has some drawbacks mainly related to the high energy consumption and operation costs. The high energy demand of membrane processes is primarily due to: i. membrane aeration to scour the membrane surface and keep it clean; ii. pumping sludge from the main biological reactor through the membrane modules; iii. they are pumping for permeate extraction and backwashing (Judd and Judd, 2006). The membrane fouling increases the energy demand and the need for chemical requirements for the cleanings, thus further influencing the operational costs. These drawbacks could be related to the adopted treatment scheme and hamper the ultrafiltration's wider spread applicability. Therefore, there is a need to investigate the best way of operating an ultrafiltration membrane for producing water for agriculture scope (Mannina et al., 2022). The need for a trade-off achievement between the effluent quality and operational costs is also mandatory in view of making the adoption of ultrafiltration membranes environmentally and economically sustainable. This abstract compares the performance of two pilot plant configurations operated in parallel. Specifically, the UF membrane was operated as MBR (Configuration I) and tertiary treatment after a CAS system (Configuration II). A comparison has compared WW treatment performance and permeate quality according to the EU 741/2020 regulation. Nitrous oxide (N_2O) emission was measured. Further, the carbon footprint and operational costs have been quantified.

2. MATERIALS AND METHODS

Two pilot plant configurations (Configuration I and Configuration II) treating real wastewater and operating in parallel were built at the Water Resource Recovery Facility (WRRF) of Palermo University (Mannina et al., 2021a;b).The two configurations have the same biological treatment unit consisting of a Fixed Film Activated Sludge – Intermittent Aeration (IFAS-IA) reactor (225 L) devoted to carbon and nitrogen removal from an influent flow rate of 50 L h^{-1} (Q_{IN}) (Figure 1).

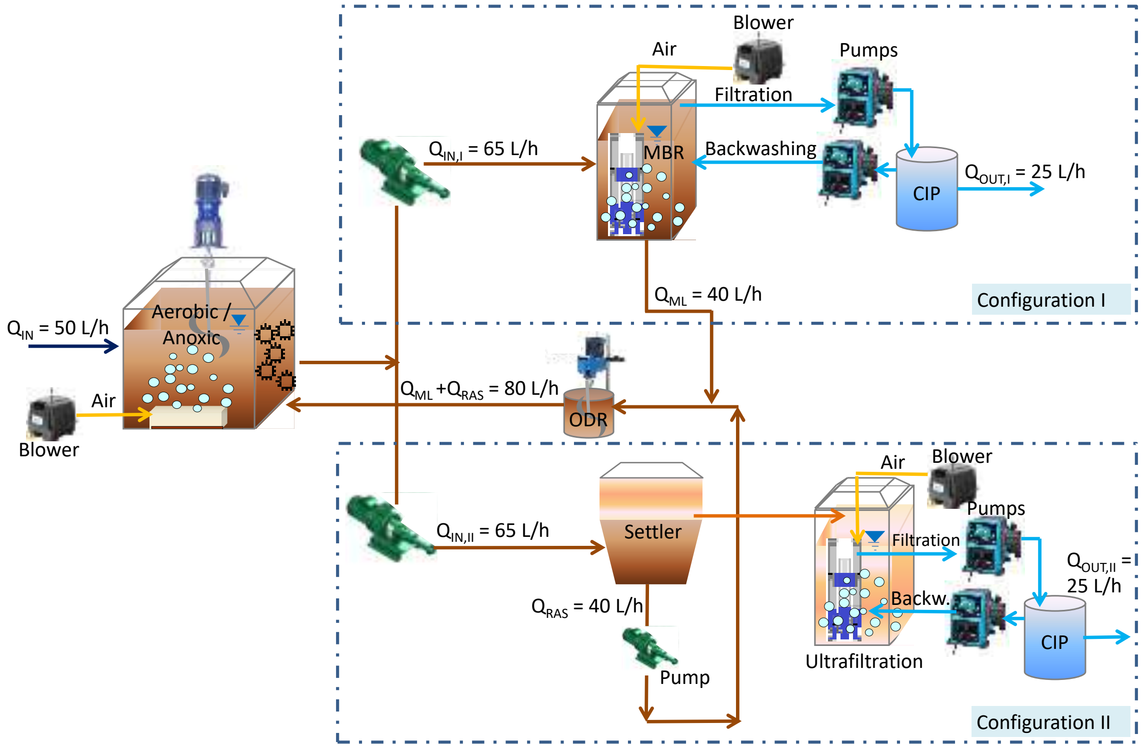

Figure 1. Schematic layout of the pilot plant and specification of Configuration I and II

The combination of suspended and attached biomass inside the IFAS-IA reactor was guaranteed by 40 litres of carriers (0.95 g/cm^3 density and 500 m^2/m^3 specific). The working mode of the IFAS-IA reactor was 40 minutes of aeration on and 20 minutes off. A flow rate of

65 L h^{-1} of mixed liquor was pumped from the IFAS-IA reactor to each plant configuration ($Q_{IN,I}$ and $Q_{IN,II}$ to Configuration I and II, respectively). For Configuration I the solid/liquid separation took place using a membrane bioreactor (MBR) (48 L). The MBR had a hollow fiber ultrafiltration membrane module (0.03μm porosity and 1.4 m^2 surface). From the bottom of MBR 40 L h^{-1} of mixed liquor (Q_{ML}) was recirculated back to the IFAS-IA through the Oxygen Depletion Reactor (ODR) to reduce the oxygen mass (Figure 1).

For Configuration II a vertical settler (V = 46 L) was devoted to the solid/liquid separation, followed by a tertiary unit equipped with a hollow fiber ultrafiltration membrane module. From the bottom of the settler 40 Lh^{-1} of recirculated activated sludge (Q_{RAS}) was pumped back to the IFAS-IA through the ODR (Figure 1).

The permeate flow rate from Configuration I and II was equal to 25 L h^{-1} ($Q_{OUT,I}$ and $Q_{OUT,II}$). For both configurations, the hollow fiber ultrafiltration membrane module had the same features The membranes were operated under filtration cycles (9 min filtration and 1 min backwashing) using peristaltic pumps (Watson Marlow Qdos 30 Universal pumps, 30 L h^{-1}). The membrane reactors had a clean-in-place (CIP) tank for ordinary backwashing. During the monitoring campaign, influent and effluent samples from each plant configuration were withdrawn two times per week in view of analysing total COD -TCOD, soluble COD - sCOD, ammonia - NH_4-N, total nitrogen - TN and orthophosphate - PO_4. The analysis was performed according to Standard Methods (APHA, 2012). Further, membrane fouling was monitored by measuring the total resistance to the membrane filtration. Dissolved and gaseous N_2O concentrations were evaluated using a gas chromatograph (GC) (Agilent 8860) with an electron capture detector (ECD). In view of verifying the class of EU 741/2020 regulation the permeate quality from each configuration was also monitored two times per week in terms of BOD_5, TSS concentrations, turbidity and *E. coli*. *E. coli* concentration was measured using method F as proposed by IRSA – CNR. Turbidity was measured by using a portable Hanna (USA) HI93703 turbidimeter. Further, the carbon footprint quantification was performed considering both direct (due to energy consumption) and indirect (due to energy consumption) emissions, according to Boiocchi et al. (2023). The reclaimed water quality index ($RWQI_1$) proposed by Cosenza et al. (2022) was used to compare the treatment performance of each configuration in terms of water reuse.

3. RESULTS AND DISCUSSION

For the sake of conciseness, this study will only show and discuss the results of RWQI1 and carbon footprint.

Figure 2 shows the results of $RWQI_1$ and the carbon footprint for each configuration. Data from Figure 2a show that both configurations allowed to achieve $RWQI_1$ lower than Class A quality according to EU 741/2020 regulation. Since the $RWQI_1$ represents the weighted sum of the pollutant concentrations contained in the water to be reused, the result above means that the quality of the obtained water was excellent according to EU regulation (Regulation 2020/741). Indeed, both configurations provided water with null *E.coli* concentration, average BOD_5 and TSS concentrations below 10 mg/L, and turbidity below 5 NTU. By comparing the two configurations one can observe that Configuration II provided the best result with the lowest $RWQI_1$ value equal to 0.43 kg pollutant/year (Figure 2a). Results obtained in terms of $RWQI_1$ were confirmed even for the carbon footprint. Indeed, the lowest carbon footprint (0.38 gCO_{2eq}/m^3) was obtained for Configuration II. Direct emissions of Configuration II were equal to 0.25 gCO_{2eq}/m^3, which is almost 1/3 lower than that of Configuration I (0.32 gCO_{2eq}/m^3). At the same time, indirect emissions were equal to 0.17 and 0.125 gCO_{2eq}/m^3 for Configuration I and Configuration II, respectively. This latter result was mainly due to the lower membrane fouling of Configuration II compared to Configuration I, which reduced energy demand.

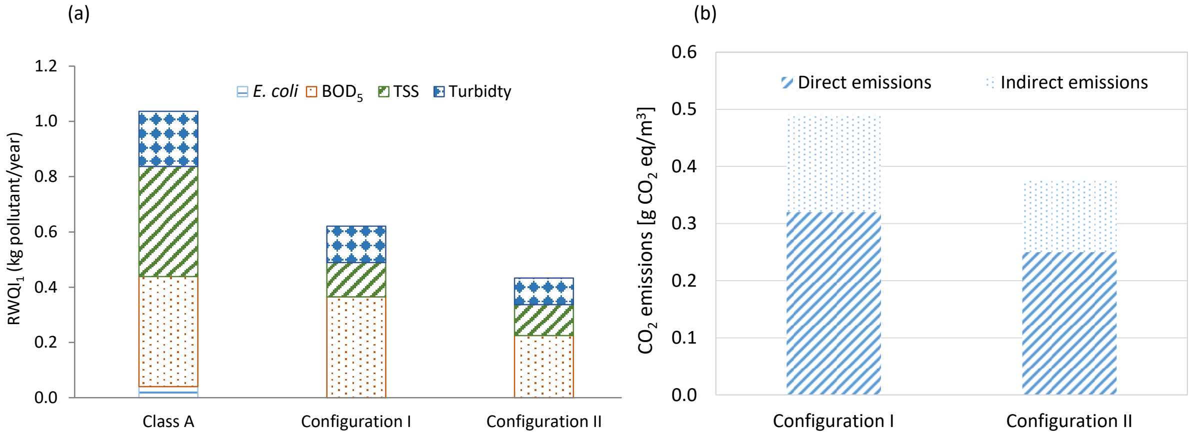

Figure 2 - RWQ₁ for each configuration compared to the Class A quality of EU 741/2020 regulation (a); carbon footprint in terms of direct and indirect emissions for each configuration (b)

CONCLUSIONS

This study compares two pilot plant configurations treating real wastewater (Configuration I and Configuration II) and producing water for agriculture. The common biological treatment among the two configurations was operated according to an Integrated Fixed Film Activated Sludge – Intermittent Aeration (IFAS-IA) reactor. The water produced from both configurations can be classified as Class A of EU 741/2020 regulation. Configuration II provided the best results in terms of $RWQI_1$ and carbon footprint.

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