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Reclaimed water for fertigation: sustainability assessment in two Mediterranean case studies within the European Innovation Deal

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Abstract

Water scarcity has become a major concern worldwide due to global warming and climate change impacts. In this context, assuring food production for an increasing population entails improving water management considering, among others, potential new water sources. In this sense, the use of anaerobic membrane bioreactor (AnMBR) technology for urban wastewater can contribute to alleviate droughts by reusing the water and nutrients embedded in the effluent directly in agriculture (fertigation) in line with Circular Economy principles. Moreover, the combination of AnMBR technology and fertigation reduces CO_2 emissions due to the organic matter valorization and the partial avoidance of mineral fertilizer requirements. However, AnMBR and fertigation still face technological and regulatory barriers that need to be solved. These bottlenecks were tackled within the first Innovation Deal approved by European Commission on 2016 developing several case studies for water reuse systems. Results in Oliva WWTP (Spain) and Peschiera-Borromeo WWTP (Italy) showed that reclaimed water can be considered a reliable water and nutrient supply source, demonstrated a positive economic balance (up to 376 k€·year^{-1}) and exhibited significant reductions or even savings in CO_2 emissions (up to -898.9 $tCO_2 \cdot year^{-1}$).). A new stakeholder, Water Reclaimed Manager, was also proposed to be in charge of supplying reclaimed water with appropriate quantity and quality to end-users and. This new agent would also be responsible of developing and implementing a Water Reuse Risk Management Plan.

Keywords

Agricultural water reuse; Anaerobic digestion; Membrane technology; Reclaimed water; Nutrient recovery and reuse; Sustainability assessment

1. Introduction

The ever increasing global demand for food means that agriculture is becoming ever more intensive (Clar et al., 2018; Hussain et al., 2019) with a growing demand for water extraction and fertilizers. However, this additional pressure on water resources is happening in the midst of conditions of climate change, which are expected to affect rain patterns and cause water scarcity in many regions (Ledger et al., 2012).

It has been reported that between 1976 and 2006 the percentage of the world's surface and the population affected by drought rose by 20% with associated economic losses of €100 billion. In the EU, 11% of the population and 17% of its territory have already suffered serious droughts (Collins et al., 2009). Water scarcity and limited availability of essential nutrients, such as phosphorus (P) now compose a serious risk to food production. By way of example, phosphate rock and P were included in the EU's Critical Raw Materials list in 2014 and in 2017, respectively (European Commission, 2017, 2014). The Mediterranean EU countries are characterized by high levels of food production (Spain and Italy provided 33.5% and 51% of EU's fruit and vegetables, respectively, in 2017), but also by water shortages and dependence on imported P-based fertilizers.

In this context of global water scarcity, it is now essential to make more efficient use of the available resources. In 2007, the EU recommended water saving and efficiency as priority strategies for its member states in order to manage scarcity and drought (European Commission, 2007) and in 2012 it adopted the Blueprint to Safeguard Europe's Water Resources (European Commission-DG ENV, 2012). This report recognized that the use of *reclaimed water* (treated before re-use) has a smaller environmental impact than other alternatives, i.e. water transfers or desalination, while it also has financial and social benefits. Since then, interest has grown in this approach to water management and several documents, reports and scientific papers have been published on the benefits, challenges and issues still to be addressed in order to take full advantage of reclaimed water. For example, in June 2019 the EU Council agreed on its general approach to the Proposal for a Regulation of the European Parliament on the minimum requirements for water reuse (Council, 2019). This proposed regulation aims to overcome some of the bottlenecks that still restrict water reuse in the EU and clarifies the competent authorities' obligations, harmonizes water quality requirements within the UE and lays down the need to design and implement a Water Reuse Risk Management Plan to protect the environment and human and animal well-being.

Applying Circular Economy (CE) principles to the water value chain is also a key EU policy (European Commission, 2015) and could help to achieve economic and environmental objectives (Sgroi and Vagliasindi, 2018). As a result of the adoption of CE fundamentals, the conventional concept of wastewater treatment plants (WWTPs) is shifting to recovering not only water resources (WRRF) but also its embedded materials, energy and nutrients (Puyol et al., 2017).

Wastewater reclamation still faces a number of different barriers, including uncontrolled freshwater extraction, inadequate water pricing policies and legislation, which discourage water reuse (WWAP, 2017) and constitute a risk to human wellbeing and the environment. The CE could help to improve water pricing policies by taking advantage of nutrients and the water itself. Nutrients are essential in agriculture for healthy crops, although their overuse pollutes the environment and degrades ecosystems. As both Nitrogen (N) and P are the main components of wastewaters and fertilizers, nutrient management needs to be tackled from a global perspective to avoid pollution and maintain sustainable food production. The environmental benefits of using reclaimed water and nutrients for *fertigation* (water plus nutrients) include not only conserving freshwater sources but also reducing energy consumption for P extraction (2.11 kWh·kg P^{-1} according to Gellings, C. W and Parmenter, 2004) and for industrial ammonia-based fertilizer production (19.3 kWh·kg N^{-1} by the Haber-Bosh process according to Perry L McCarty et al., 2011). Recycling P from wastewater to farmland is thus of great interest, since this is an irreplaceable, if limited, element for crop growth.

Anaerobic membrane bioreactors (AnMBR) have been successfully studied as potential substitutes for conventional WWT processes (Becker et al., 2017; Dereli et al., 2012; Galib et al., 2016; Kamali and Khodaparast, 2015; Mei et al., 2016; Ozgun et al., 2013) since they combine the advantages of membrane filtration with those of anaerobic processes. AnMBR improves energy balances, maximizes resource recovery and reduces the carbon footprint and waste (Pretel et al., 2016a). The combination of AnMBR with fertigation would thus reduce the need for water extraction and chemical fertilizers, with financial savings and environmental benefits. AnMBR would therefore drastically improve the water-energy-nutrient nexus (Lazarova V and Choo K-H, 2012).

With the aim of studying in depth whether regulatory barriers in the EU legislation or industrial development of CE really existed, the European Commission (EC) launched the Innovation Deal (ID) initiative in 2016. The proposal entitled *Sustainable wastewater treatment combining anaerobic membrane technology and water reuse* was one of the first pilot IDs and focused on whether the existing legislation (EU, national or regional) could prevent the application of AnMBR technology to urban WWT to allow the reuse of effluent and its embedded nutrients for fertigation. This ID consortium consisted of 14 partners from 5 European member states (Portugal, Spain, Malta, Italy and France) and included national and regional authorities, universities, research centers, innovators and end-users. The EC was represented by staff from the Directorate-General for Research and Innovation, the Directorate-General for Agriculture and Rural Development and the Directorate-General for the Environment.

This ID's work included the analysis of different case studies in the Mediterranean region (Italy and Spain) on a WWT system designed to maximize resource recovery and minimize environmental impact according to CE principles. The proposed system consisted of a combination of AnMBR technology and fertigation. Different scenarios were examined in each case study and were compared to the current case of no water reuse. The results obtained, which showed the economic and environmental benefits of reusing water for fertigation with AnMBR technology, are the subject of the present paper.

2. Material and Methods

Each case-study encompassed different scenarios, one of which included AnMBR technology. A four-step assessment methodology was developed to analyze different WWT scenarios: (i) water balance, (ii) nutrient balance, (iii) economic analysis and (iv) estimating CO_2 emissions.

2.1. Water balance

In the first step, the *net crop requirements* or *net provision* ($m^3 \cdot ha^{-1} \cdot year^{-1}$) are calculated, taking into account the type of crop and the location of the site, since meteorological (effective precipitation) and soil data (available water stored in the soil) exert a considerable influence on water availability. Once the net crop requirements are obtained, a water balance is applied to the irrigation network in order to calculate the *gross irrigation volume* (V_B in $hm^3 \cdot year^{-1}$) that will be extracted from the water source, since transport, distribution and irrigation networks suffer water losses, known as transport network return flows (r_t), distribution network return flows (r_d) and irrigation return flows (r_a). There is also a water loss associated with evaporation along the irrigation network: water evaporation in transport network (p_t), water evaporation in distribution network (p_d) and water evaporation in the irrigation volume applied to the land (p_a) (see Figure 1).

Figure 1. Scheme of water and nutrient balances applied to the transport, distribution and irrigation network

Evaporation water losses are determined experimentally throughout the year (measuring campaigns by the Júcar River Basin Authority) and return flows are calculated as follows:

$$r_t = V_B - V_D - p_t \qquad \text{(Eq. 1)}$$

$$r_d = V_D - V_P - p_d \qquad \text{(Eq. 2)}$$

$$r_a = V_P - V_N - p_a \qquad \text{(Eq. 3)}$$

where V_D (hm^3·year^{-1}) is the irrigation water volume influent to the distribution network, V_P (hm^3·year^{-1}) is the water volume applied to cropland and V_N (hm^3·year^{-1}) is the net irrigation volume, all as measured on site.

Taking into account the water losses in the water flow sections, an efficiency percentage was obtained for the transport (e_t) and distribution network (e_d) as well as for the irrigation method (e_a) (Eqs. 4 to 6). These efficiency factors were used for all conversions between gross and net irrigation volumes.

$$V_D = V_B \cdot e_t \qquad \text{(Eq. 4)}$$

$$V_P = V_D \cdot e_d \qquad \text{(Eq. 5)}$$

$$V_N = V_P \cdot e_a \qquad \text{(Eq. 6)}$$

2.2. Nutrient balance

During the nutrient balance the total amount of nutrients supplied with the irrigation water is calculated, as well as the supplementary mineral fertilizers needed to provide the crops with the required nutrients. The balance also evaluates the total nutrients released into water bodies and their environmental impact. The balance is applied taking into account that water losses by evaporation give rise to higher nutrient concentrations throughout the water network (Eq. 7, Figure 1).

$$V_B \cdot C_B + F = r_t \cdot C_t + r_d \cdot C_d + r_a \cdot C_a + f + U \qquad \text{(Eq. 7)}$$

where *C* represents nutrient concentration (N or P), *F* is the fertilizer surplus, *r* is the return flows and subscripts *B*, *t*, *d* and *a* indicate the water flow section where they are identified, while *f* considers mineral fertilizer losses and *U* represents the crop's nutrient uptake.

The following assumptions were made:

- $V_P \cdot C_d + F = U + r_a \cdot C_a + f$: total nutrients provided by net irrigation water ($V_P \cdot C_d$) and mineral fertilizers (F) consisting of the crop's nutrient uptake (U) nutrient losses related to return flow in cropland ($r_a \cdot C_a$) plus mineral fertilizer losses (f).

- $C_N = C_a$: nutrient concentration in the irrigation return flow (r_a) is equal to nutrient concentration in the net irrigation water volume required by the crop (V_N).

2.3. Economic balance

Figure 2 shows the elements included in the economic balance designed to evaluate the sustainability of AnMBR for fertigation, with the different water, nutrient and monetary flows in a water reuse system. A new entity has been included: the Reclaimed Water Manager (RWM), as proposed by the authors, in line with the new EU regulations, as the managing body responsible for controlling and supervising the reuse system. The RWM would thus be in charge of environmental and health protection, including drawing up the Water Reuse Risk Management Plan.

Figure 2. Water (full line), nutrients (dotted line) and monetary flows (dashed line) for an agricultural water reuse system.

The different flows shown in Figure 2 are described as follows:

- Nutrient-rich wastewater reaches the WWTP via the sewage network and collectors. Based on the "*polluter pays principle*", there is a parallel monetary flow from the users (polluters) to the WWTP.
- Treated water and its nutrients enter the Reclaimed Water Treatment Plant (RWTP) for additional treatment (e.g. further filtration, disinfection and/or advanced oxidation processes) to produce good quality reclaimed water.
- The water to be reused is pumped into the irrigation transport/distribution network. Farmers can also use other water sources, such as groundwater and/or surface water, which have to be paid for.
- Depending on the crop requirements, farmers might need to add mineral industrial fertilizers, which creates a monetary flow to fertilizer producers. If enough nutrients are present in the reclaimed water, this monetary flow can be reduced or even disappear.

- The RWM would be paid by the farmers for controlling the water reuse system and ensuring enough good-quality water is provided, which opens a new market niche and business opportunity. The RWM will pay the RWTP for the water and nutrients and for using the pumping system. The RWM could also pay the WWTP for any additional treatment needed. In cases where savings can be made in wastewater treatment (WWT) (e.g. avoiding or reducing nutrient removal) or in discharge fees to surface or marine water due to water reuse, the WWTP might pay the RWM.
- The authorities could subsidize the system through the RWM, based on environmental, social and territorial considerations.

The total cost associated with running the WWT and providing reclaimed water for fertigation (C_{Total} , €·year^{-1}) was obtained as follows:

$$C_{\text{Total}} = C_{\text{WWT}} - C_{\text{Energy recovery}} + C_{\text{Chemical precipitation}} + C_{\text{treat\_for\_reuse}} + C_{\text{Pumping}} + C_{\text{Fertilizers}} + C_{\text{Discharged fee}} \qquad \text{(Eq. 8)}$$

where C_{WWT} is the cost of treating wastewater to meet Urban Wastewater Treatment Directive (UWWTD) (91/271/EC) requirements, $C_{Energy\ recovery}$ is the saving associated with the energy recovered as methane during wastewater treatment, $C_{treat\_for\_reuse}$ is the additional treatment cost of reclaimed water reuse, $C_{Discharge\ fee}$ is the cost of discharging treated wastewater into water bodies, $C_{Pumping}$ is the energy cost for pumping a natural source of water (surface water or groundwater) or reclaimed water and $C_{Fertilizers}$ is the cost of buying fertilizers.

The cost balance of the RWM (B-RWM) was calculated by adding the cost flows in Figure 2:

$$\text{B-RWM} = \pm 2\,(€) + 5(€) - 3\,(€) - 4\,(€) + 8\,(€) \qquad \text{(Eq. 9)}$$

Where Flow 8 (subsidies) was assumed to be zero. The current price paid by polluters and farmers (current scenario, no water reuse) was kept constant in all the scenarios studied. Polluter prices were calculated according to the individual characteristics of each case, and the farmer's price was calculated as follows:

$$\text{Farmer's price} = C_{\text{Fertilizers}} + C_{\text{Pumping}} \qquad \text{(Eq. 10)}$$

The flow from WWTP to the RWM (Flow 2) was calculated as the difference between the (constant) paid polluter price and the real cost. Savings were made in wastewater treatment or by the absence of chemical precipitation. The flow from farmers to the RWM (Flow 5) was calculated in the same way as the difference between the farmer's price, which was to remain constant, and the real farming costs, i.e. since the purchase of mineral fertilizer was partially or totally avoided, the RWM could profit from the associated savings.

2.4. Unit costs and energy consumption

Commercial fertilizer prices and energy consumption in Spain was estimated as shown in Table 1**Error! Reference source not found.**, assuming a WWTP energy cost of 0.125 €·kWh^{-1}. Energy consumption of 0.26 kWh·m^{-3} was considered for the CAS system with nutrient removal in the Italian case (value provided by system experts), together with an energy cost of 0.14 €·kWh^{-1}. Costs of 4.35 €·kgP$_{\text{removed}}^{-1}$ were considered for the consumption of chemical reagents during P removal (data provided by EPSAR, Spanish public body in charge of WWT in Valencia) and 0.006 €·m^{-3} for chemical membrane cleaning related to AnMBR technology (Pretel et al., 2016a). A pumping energy cost of 0.137 €·kWh^{-1}was considered for a pumping height of 60 m and 9.5 m for groundwater and reclaimed water, respectively.

Table 1. Cost of most usual mineral fertilizers and unitary treatment energy needs and energy reuse of WWT

It should be noted that: (i) the discharge fees applied in Valencia ($C_{Discharged\ fee}$) are on average 0.004 €·m^{-3} and 0.0135 €·m^{-3} for discharging water into coastal and inland water bodies, respectively. (ii) Italy does not apply discharge fees ($C_{Discharged\ fee}=0$). (iii) C_{WWT} already includes the cost of P chemical precipitation ($C_{Chemical\ precipitation}$) and disinfection ($C_{treat\_for\_reuse}$) in Peschiera Borromeo, due to regional regulations. (iv) C_{WWT} includes the cost of chemicals for membrane cleaning.

2.5. Carbon dioxide emissions

CO_2 assessment included: CO_2 emissions related to WWT energy consumption ($CO_{2treatment}$), pumping ($CO_{2pumping}$) and fertilizer production ($CO_{2fertilizers}$), as well as the

CO_2 emissions avoided by energy recovered as biogas ($CO_{2biogas}$). The WWT-associated CO_2 emissions were based on the energy consumption given in Section 2.4**Error! Reference source not found.**, considering a European average electricity specific emission factor of 0.2958 kg $CO_2 \cdot kWh^{-1}$ (EEA, 2018). The energy required for fertilizer production was assumed to be 19.3 $kWh \cdot kgN^{-1}$ by the Haber-Bosh Process (Perry L. McCarty et al., 2011) and 2.11 $kWh \cdot kgP^{-1}$ (Gellings and Parmenter, 2004).

Total CO_2 emissions ($tCO_2 \cdot year^{-1}$) were calculated as follows:

$$\text{Total } CO_2 \text{ emissions} = CO_{2treatment} + CO_{2pumping} + CO_{2fertilizers} - CO_{2biogas} \quad (Eq.\ 11)$$

2.6. Case studies description

2.6.1. Oliva WWTP

2.6.1.1.Site description

With a WWT flow (V_T) of 5.5 $hm^3 \cdot year^{-1}$ (39 500 population equivalent (p.e.)), Oliva WWTP has an extended aeration (EA) process without P removal by precipitation. The WWTP is in Oliva (Valencia, Spain) and its effluent is discharged into the Mediterranean Sea. It is surrounded by 582 hectares of agricultural land, supplied with 3.4 $hm^3 \cdot year^{-1}$ by ground water extraction and flooding irrigation. This land is a non-sensitive area, according to UWWTD, but a vulnerable zone according to the Nitrates Directive (NiD) (91/676/EC). The polluter price in this case included $C_{Discharged\ fee}$ together with the cost of the treatment.

2.6.1.2.Water and nutrients needs

Citrus fruit is the most abundant crop in the study area. Citrus trees need water the whole year round with a net requirement of 3.145 $hm^3 \cdot ha^{-1}$, according to the data provided by the Jucar River Basin Authority (CHJ).

Citrus N and P needs were considered as follows: 260 kg $N \cdot ha^{-1} \cdot year^{-1}$ and 80 kg $P \cdot ha^{-1} \cdot year^{-1}$for flood irrigation and 220 kg $N \cdot ha^{-1} \cdot year^{-1}$ and 70 kg $P \cdot ha^{-1} \cdot year^{-1}$ for drip irrigation (Conselleria d ’ Infraestructures , Territori i Medi Ambient Conselleria de Infraestructuras, 2018; Quiñones, A., Martínez-Alcántara, B., Primo-Millo, E. and Legaz, 2013).

2.6.1.3.Analyzed scenarios

The scenarios studied for Oliva WWTP are shown in Figure 3. . SI (a) represents the current situation, in which all the treated wastewater is discharged into the environment, while all the water needed for irrigation is extracted from the ground. SI thus includes pumping costs as well as the continuous impact on the availability of fresh water.

EA energy consumption is in the range of 0.35-0.42 $kWh \cdot m^{-3}$ (Table 1). In the case of the Oliva WWTP, due to the treatment flow and the extent of N removal, a value of 0.375 $kWh \cdot m^{-3}$ was considered. Although SI meets the UWWTD requirements, it is still far from complying with CE objectives, since water, energy and nutrients are not reused, and fertigation water can be used for agricultural water and nutrient demands, as shown in Scenarios II, III and IV (Figure 3.), where no groundwater is extracted, with consequent savings. SII includes fertigation after wastewater treatment, with reclaimed water that contains concentrations of N and P of 15 and 6 $mg \cdot L^{-1}$, respectively. In SIII it is assumed that 100% of WWTP inflow is treated by AnMBR technology instead of EA, providing effluent richer in N and P (50 and 8 $mg \cdot L^{-1}$, respectively, the usual values for nutrient concentrations in WWTPs influent, according to EPSAR) and biogas generated by anaerobic digestion of organic matter in wastewater. Although Oliva WWTP discharges into a non-sensitive area, an SIV was evaluated (Figure 3.) in which wastewater is treated through two parallel lines (AnMBR and EA) to reduce total nutrients released into the environment.

Figure 3. Scenarios in Oliva WWTP case study: (a) SI, (b) SII, (c) SIII and (d) SIV

2.6.2. Peschiera Borromeo WWTP

2.6.2.1.Site description

The Peschiera Borromeo WWTP is currently treating an average inflow rate of 78.84 $hm^3 \cdot year^{-1}$ (566000 p.e.) through two water lines that receive wastewater from Milan and neighboring municipalities. Line 1 consists of a conventional activated sludge (CAS) process followed by tertiary treatment (2 stage upflow biological filtration with nitrification-denitrification and final disinfection with peracetic acid) while line 2 consists of CAS with nutrient removal and UV disinfection. This WWTP is located in the municipality of Peschiera Borromeo (Italy) discharging into the Lambro River, which was declared a sensitive area according to the UWWTD and a vulnerable zone according to the NiD. It should be noted that the Italian regulations set the N_T and P_T standard for water reuse at 15 and 2 $mg·L^{-1}$, respectively, so that all WWTPs must remove nutrients before reuse. This is a major barrier to possible fertigation and in this case study the polluter price includes the cost of chemical precipitation and disinfection.

2.6.2.2.Water and nutrients needs

The surrounding agricultural land which could potentially be irrigated with reclaimed water has an extension of 1500 ha and its water demand is 12.03 $hm^3·year^{-1}$. This demand could be covered either by surface water or by a flow rate from water line 2 of the WWTP. The plant is located in a peri-urban agricultural park (Parco Agricolo Sud Milano) and the main crop is tomatoes. The average water requirements are 7.318 $hm^3·ha^{-1}$ from April to September (183 days). Tomato N and P needs for drip irrigation systems are 160 kg $N·ha^{-1}·year^{-1}$ and 20 kg $P·ha^{-1}·year^{-1}$ (Conselleria d ' Infraestructures , Territori i Medi Ambient Conselleria de Infraestructuras, 2018)

2.6.2.3.Analyzed scenarios

The scenarios studied in the Peschiera Borromeo WWTP are given in Figure 4.**Error! Reference source not found.** SI represents the current situation, in which all the treated wastewater is discharged into the environment, while all the irrigation water is extracted from a fresh water source, reducing resource depletion and affecting the surrounding ecosystem. Although a large amount of energy is required for the WWT, SI is the most common situation in many parts of Italy due to the restrictive legislations, long distances, unfavorable slope between the WWTPs and irrigation areas, and the high monitoring and distribution costs (Ventura et al., 2019).

In SII a fraction of water flow treated in the CAS process bypasses the nutrient removal process and is used for fertigation. This treatment scheme means that the bypassing flow can be modified or even cancelled according to the demand for nutrients. The possibility of mixing treated water is also included (dashed line). SIII is proposed with the aim of maximizing energy and nutrient recovery, complying with CE principles. In this scenario, a fraction of the influent is treated by AnMBR, which could reduce the total WWT energy consumption due to biogas production and the generation of a nutrient-rich effluent that would notably reduce fertilizer costs. In this scenario and in SII, the modification of the Italian regulations is assumed to either approve land application as a wastewater post-treatment, or the use of reclaimed water as a fertilizer product.

SIV was designed as a contrasting treatment scheme where all wastewater is treated through a CAS system with nutrient removal and water containing nutrients is reused for agriculture. SIV represents the current situation of some Italian WWTPs, such as Milano San Rocco and Milano Nosedo, where part of the effluent is used for irrigation and farmers supply their own fertilizers.

Figure 4. Scenarios in Peschiera Borromeo WWTP case study: (a) SI, (b) SII, (c) SIII, (d) SIV

3. Results and discussion

3.1. Efficiency factors

Preliminary studies allowed for the calculation of efficiency factors for conversion between gross and net irrigation volumes, which were applied in this study and are shown in Table 2. Peschiera Borromeo is more efficient since the transport network consists of pipelines and the irrigation method used is the drip system. In the case of Oliva, the pipeline distribution and drip irrigation systems were included as an optimized version of each scenario, assuming transport, distribution and application efficiencies of 95%, 97% and 97%, respectively.

Table 2. Return flows and supplied water efficiency for both Oliva and Peschiera Borromeo case studies.

3.2. Oliva WWTP

3.2.1. Water balance

The current situation is represented by SI. In this scenario, 3.36 $hm^3 \cdot y^{-1}$ of groundwater are used for irrigation (Figure 3), which intensifies natural resource depletion. This consumption can be avoided by using reclaimed water for irrigation, which would improve the conservation of water bodies. In these Scenarios II and III, 61.3% of the wastewater treated in the Oliva WWTP would be reused.

The calculated efficiency factors (Table 2) show that there is high water loss through the irrigation network as a consequence of return flows and the irrigation method used (flooding), which results in a total supplied water efficiency of 54.5%. The application of an optimized irrigation system (pipeline irrigation network and drip feed) would significantly reduce water losses from 1.32 $hm^3 \cdot year^{-1}$ to 0.18 $hm^3 \cdot year^{-1}$ with the consequent network efficiency increase.

The results show that irrigation system optimization is a key factor in minimizing water losses. The water balance calculated for the 4 scenarios in Oliva WWTP with an optimized irrigation network, as expected, showed a smaller water reuse flow of 2.05 $hm^3 \cdot year^{-1}$.

3.2.2. Nutrient balance

Used as the baseline, SI discharged treated wastewater into coastal waters, thus losing nutrients into the environment. In this scenario, the total crop nutrient demand is met by mineral fertilization.

The smaller discharge flow in SII reduces nutrient losses to the environment: 42.2% less N and 35.4% less P (Figure 5). At the same time, SII recovers the P contained in the reclaimed wastewater: 20.6 kg $P \cdot ha^{-1} \cdot year^{-1}$, reducing mineral P addition by 29.4% (Figure 5a).

The AnMBR results in SIII show that it reduces P losses by 18.9% (SIII compared to SI, Figure 5a) while N discharged into the environment increases from 118.7 $t \cdot year^{-1}$ in SI to 178.6 $t \cdot year^{-1}$ in SIII. The reason behind this result lies in the fact that the higher N content in the AnMBR effluent is more significant (from 15 to 50 $mg \cdot L^{-1}$) than for P concentration (from 6 to 8 $mg \cdot L^{-1}$, Figure 3). As a result, the reduction in discharged flow in SIII compensates for the increase in the effluent's P concentration, whereas in the case of N its higher AnMBR effluent concentration causes higher N losses, even though the discharge is smaller. In any case, SIII can reduce the N and P added by mineral fertilizers by up to 71.6% and 39.2%, respectively (Figure 5a). SIV has the same mineral addition needs as SIII and reduces nutrient losses with respect to Scenarios I and III.

Figure 5. a) Nutrients discharged into the environment in the 6 scenarios proposed in Oliva WWTP; b) Results of nutrient balance applied to cropland in the 6 scenarios proposed in Oliva WWTP

It should be noted that the application of an optimized irrigation system under all circumstances not only reduces water losses but also nutrient losses, and therefore the amount of N and P released through the network was lower in the 4 optimized scenarios (Figure 5). This entails an extra environmental benefit for groundwater bodies.

3.2.3. Economic balance

The results obtained from the economic analysis are presented in Table 3. Operational costs of wastewater treatment with AnMBR technology are 63.4% lower in SIII and 39% in SIV. The coastal body discharge fee in Scenarios II to IV is reduced in proportion to the amount of water reclaimed. Disinfection costs only apply in SII, since membranes are used in Scenarios III and IV. In all three scenarios, a pumping cost is required but groundwater extraction pumping costs disappear. Fertilizers costs are also reduced by fertigation, especially when the reclaimed wastewater has a higher level of nutrients obtained by AnMBR.

Table 3. Economic results from the 4 scenarios studied in Oliva WWTP

As explained above, as it was proposed to maintain the cost for polluters and farmers in all cases equal to that of SI (278.9 and 202.0 $k€\cdot year^{-1}$, respectively), a flow from the WWTP to the RWM would be possible in the water reuse scenarios, since WWTP cost is actually smaller due to lower discharge fees and C_{WWT}. Similarly, due to savings in fertilizers and groundwater pumping, part of the farmers' expense could be transferred to RWM, which would have a total income of 0.029, 0.099 and 0.080 $€\cdot m^{-3}_{reused}$, for Scenarios II to IV, respectively (Table 3).

The results show the economic viability of AnMBR technology, since the total cost was reduced from 480.9 $k€\cdot year^{-1}$ (SI) to 149.4 $k€\cdot year^{-1}$ (SIII) or 212.3 $k€\cdot year^{-1}$ (SIV). At the same time, Scenarios III and IV not only meet the UWWTD and NiD requirements, but also the costs associated with fertilizers and pumping are reduced. This means the

RWM budget can be devoted to covering the reclaimed water management expenses (including the Water Reuse Risk Management Plan).

The economic balance for the 4 scenarios with an optimized irrigation network shows that while the wastewater treatment cost remains constant for Scenarios I to III (the same wastewater flow needs to be treated per year), discharge fees increase (a higher flow of treated water is discharged since a smaller water flow is reclaimed), reducing the available monetary flow from the WWTP to the RWM. On the other hand, since the reclaimed water flow is only 61% of that in the non-optimized scenarios, disinfection and pumping costs, as well as mineral fertilization needs, all decrease (Table 3). Water reuse costs are thus reduced due to the smaller water flow needed by the more efficient system.

In SI, where treated water is not reclaimed, groundwater pumping costs also decreased for the same reason. A new lower farmer price was thus established in the optimized scenarios (148.4k€·year^{-1}). The other side of this situation of reduced reuse costs is that the improved irrigation efficiency also reduces total RWM income: 37.7% in SII, 15.9% in SIII and 34.1% in SIV. The reason for this is the downscaled reuse system, while wastewater treatment costs remain the same (except for SIV, where two different technologies with two different costs are involved), together with the decrease in farmers' price due to the lower cost of optimized SI. This shows that the whole water value chain and all the stakeholders need to be taken into account when analyzing water reuse systems.

An optimized irrigation system saves water ready for reuse and reduces its cost, with a lower RWM budget. However, certain strategies could be applied to increase the RWM economic balance, including subsidies, changes in discharge fees, extension of the irrigated area, etc.

3.2.4. Carbon dioxide emissions

Carbon dioxide emissions are associated with the energy cost of mineral fertilizer production, wastewater treatment, disinfection, pumping and energy recovered as biogas. As expected, the optimized Scenarios I to III show an improvement in CO_2 emissions, due to reduced fertilizer use, pumping and disinfection (when applied)

(Figure 6). The greatest improvement, when optimized, is obtained for SI (11%). In SIV, given the fact that the amount of reused nutrients is equal to that in SIII, CO_2 emissions associated with fertilizer production are reduced in the same proportion. However, the high energy consumption in the EA process and the absence of energy recovery in this treatment produce higher CO_2 emissions than SIII.

An improvement is also observed when comparing Scenarios II to IV, with reclaimed water, to SI, where no water is reclaimed. Water reuse by conventional treatment technologies (SII) would reduce emissions by between 6.0 and 15.2% CO_2, depending on whether optimized or non-optimized scenarios are considered. AnMBR technology (SIII) would provide the biggest environmental improvement in terms of CO_2 emissions, since it would reduce them by between 74.7% and 75.3% CO_2 as a consequence of the high N content in the reclaimed water and the biogas generated.

Figure 6. CO_2 emissions for the 8 scenarios studied in Oliva WWTP

In other words, AnMBR combined with an optimized irrigation system provided the highest environmental benefit in terms of total CO_2 emissions (reduction of up to 1153 t $CO_2 \cdot year^{-1}$).

The study carried out in Oliva WWTP (Spain) showed that in this case AnMBR is suitable for the combined purpose of wastewater treatment and fertigation, since it maximizes energy and nutrient recovery and reduces both costs and CO_2 emissions. In this case study, where there was no restriction on the quantity of nutrients released into coastal waters, since it has been declared a non-sensitive area, the environmental impact of the different scenarios should be evaluated: SIII, where nutrient losses to the environment exceed those in SI or SIV, where nutrient losses are lower than SIII and SI, but CO_2 emissions are higher.

The positive impact of AnMBR would be still higher if groundwater conservation could be quantified. However, applying this technology in vulnerable zones requires risk assessment plans, including nutrient balances. Methods such as drip-feed are recommended, since they generate smaller return flows than flood irrigation.

3.3. Peschiera Borromeo WWTP

3.3.1. Water balance

In the present situation (SI) 12.03 $hm^3 \cdot year^{-1}$ of fresh water are used for irrigation (Figure 4), quite a high consumption that depletes natural resources and could be prevented with fertigation (Scenarios II and III) or irrigation (SIV), which would improve the conservation of water bodies. In these scenarios, 87% of the wastewater treated in the Peschiera Borromeo WWTP would be reused. The irrigation network in the surrounding area was designed with pipelines and the present irrigation method is by drip, showing that the results are those of an optimized irrigation system.

3.3.2. Nutrient balance

The nutrients balance clearly showed that SI is the situation in which the highest amount of nutrients is discharged into the environment (Figure 7a), which was expected in a situation that does not re-use treated wastewater. Scenarios II to IV show the expected lower nutrient discharge into the environment, with a 7.6 times smaller discharged water flow in all cases. Total N losses fall by 77.0%, 73.5% and 79.9% for Scenarios II, III and IV, respectively and with respect to SI. P losses are 79.9%, 74.3% and 82.7% less for Scenarios II, III and IV, respectively and with respect to SI. The biggest difference between the scenarios lies in the nutrient losses through the network, which are greater in SIII, with the highest nutrient content of reclaimed water.

Figure 7. a) Nutrients discharged into the environment in the 4 scenarios studied in Peschiera Borromeo WWTP; b) Nutrients balance applied to cropland in the 4 scenarios studied in Peschiera Borromeo WWTP

In SI, almost all the required nutrients are supplied by mineral fertilizers, whereas in Scenarios II, III and IV a high percentage of nutrients is provided by the reclaimed water (70%, 100% and 44%, respectively) (Figure 7b). SIII illustrates the flexibility that AnMBR technology gives to the system, where water quality regarding nutrient content can be modified by mixing with the effluent from the nutrient removal process in such a way that no mineral fertilizers are needed.

Given that there is no clear advantage regarding nutrient losses for any of the three water reuse scenarios, the economic and CO_2 emissions analysis becomes decisive in order to establish a definite comparison.

3.3.3. Economic balance

Table 4 shows the results of the economic analysis. Disinfection and nutrient removal are considered part of the wastewater treatment cost and not as an additional treatment, according to the Italian regulations, which actually requires that nutrients be removed from final effluent. This cost in SI (512.9 k€·year^{-1}) was established as the price polluters pay in all scenarios. Treatment costs are lower in Scenarios II and III than in SI (6.1% and 40.1%, respectively). All water reuse scenarios include the water pumping cost for reuse, which in this case is equal to acquiring water from natural sources, since in Peschiera Borromeo the fresh water source is surface water. Fertilizers cost decrease in the situations with water reuse, being zero when AnMBR technology is applied, which brings considerable savings in farming costs. Water reuse scenarios provide a relevant monetary flow from farmers to the RWM, especially in Scenarios II and III, due to the higher contribution of WWTP effluent to crop fertilization needs.

Table 4. Economic results of the 4 scenarios studied in Peschiera Borromeo WWTP

Although SIV gives rise to the lowest nutrient losses to the environment (see Figure 7a), it results in the highest total cost of all reuse scenarios. This is a direct consequence of the fact that nutrients are removed from the whole influent, leaving a lower nutrient content in the effluent, so that higher quantity of mineral fertilizers is needed. This, in turn, results in lower economic resources available for the RWM and shows that the current situation in some Italian WWTPs is not the optimal. AnMBR technology (SIII) could reduce the total cost of the water reuse system to 388.1 k€·year^{-1} due to the following: (i) there is no need for mineral fertilizers and (ii) treatment cost is 40.1% lower than SI because of the lower energy consumption of the biological process as well as the reduced disinfection and chemical precipitation costs.

3.3.4. Carbon dioxide emissions

Figure 8. CO_2 emissions for the 4 scenarios studied in Peschiera Borromeo WWTP

The highest CO_2 emissions were those of the current SI, followed by SIV, which represents the most frequently adopted alternative in the area (see Figure 8). Water reuse with CAS treatment (SII) provided a 46.4% CO_2 emissions reduction with respect to the present situation, while the smallest carbon footprint (-898.9 $tCO_2 \cdot year^{-1}$) was obtained for SIII, with AnMBR technology. On the one hand, the possible energy recovery as biogas is substantially higher with this wastewater treatment than with CAS. On the other hand, the avoidance of mineral fertilizers also prevented a major CO_2 emissions source. These results show that a combination of AnMBR with fertigation can notably reduce the environmental impact and the economic cost in comparison with conventional treatments such as the CAS system, provided that a high percentage of the influent can be treated by AnMBR (in this case 86.8%) and application to farmland can be considered as a post-treatment.

Given that Scenarios I and IV represent the most common situations in many parts of Europe, this results show the need to change the traditional way of looking at WWTPs, since they can be considered as resource recovery facilities in which not only water, nutrients and energy are recovered but in which also costs and the carbon footprint are minimized. At the same time, the implementation of Risk Management Plans could be (partially) financed by the savings generated when mineral fertilizer acquisition is reduced or even avoided.

4. Conclusions

Reclaimed water can be considered a reliable water and nutrient supply source, independent of seasonal drought and weather variability, thus acting as an alternative source to alleviate pressure on freshwater sources and reduce the economic and environmental cost of mineral fertilizers. However, a risk management plan is needed to ensure environmental and health safety when reclaimed water is used for fertigation.

This work has shown the positive economic balance that can be obtained in different water reuse scenarios. The authors propose that these savings be used for the development and implementation of the Risk Management Plans, carried out by the new *Reuse Water Manager*. Since AnMBR technology can also recover energy from the wastewater flow, its application presents an optimal scenario according to the Circular Economy principles and environmental sustainability. In this regard, the combination of AnMBR technology and fertigation can contribute to significant reductions of CO_2 emissions.

Lastly, in order to comply with the current legislation, future combined AnMBR and fertigation demonstration projects need to be carried out within non-sensitive areas, according to UWWTD. Moreover, to obtain comprehensive knowledge of the proposed water management scheme, demonstration actions should include environmental and health risk assessment as well as a social and economic analysis.

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Table Legends

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Table 2. Return flows and supplied water efficiency for both Oliva and Peschiera Borromeo case studies.

Table 3. Economic results from the 4 scenarios studied in Oliva WWTP

Table 4. Economic results from the 4 scenarios studied in Peschiera Borromeo WWTP

Caption for Figures

Figure 1. Scheme of water and nutrient balances applied to the transport, distribution and irrigation network

Figure 2. Water (full line), nutrients (dotted line) and monetary flows (dashed line) for an agricultural water reuse system.

Figure 3. Scenarios in Oliva WWTP case study: (a) SI, (b) SII, (c) SIII and (d) SIV

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Figure 8. CO_2 emissions for the 4 scenarios studied in Peschiera Borromeo WWTP

Figure 1

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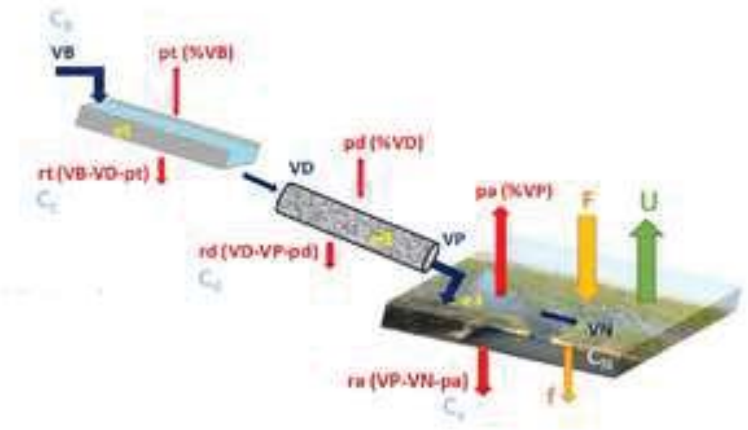

Figure 2

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Figure 3
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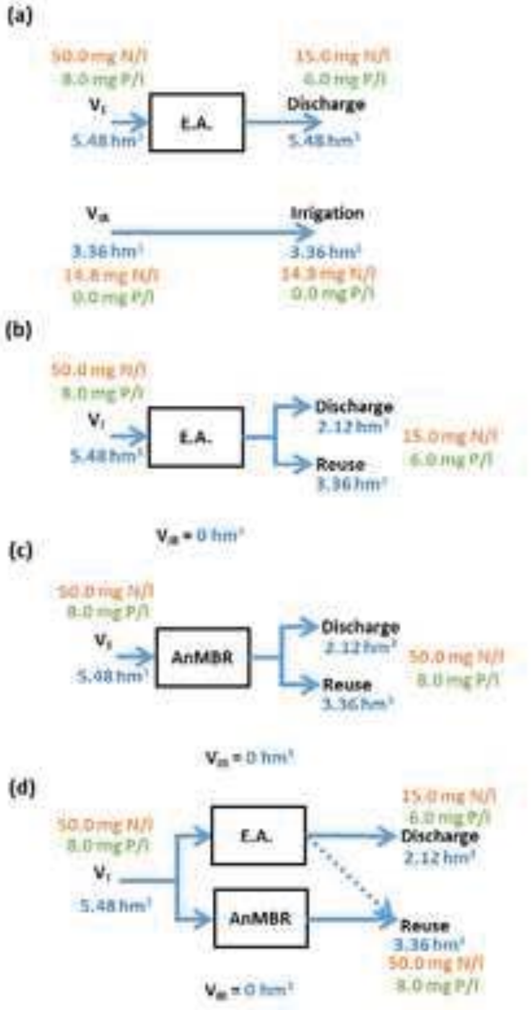

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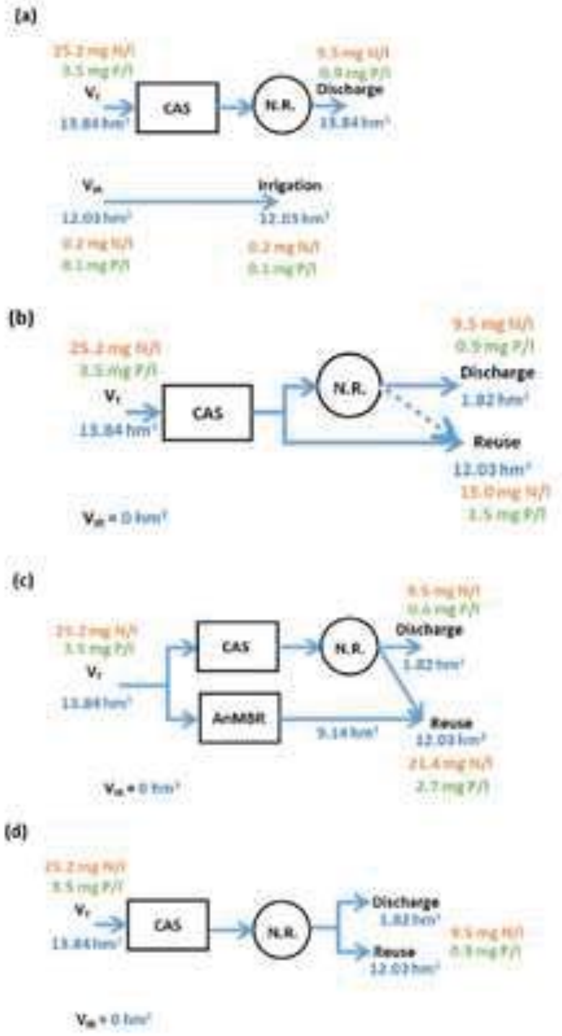
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CAS
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Discharge
13.84 hm3
Vw
12.03 hm3
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0.1 mg P/l
Irrigation
12.03 hm3
0.2 mg N/l
0.1 mg P/l
(b)
25.2 mg N/l
3.5 mg P/l
Vr
13.84 hm3
CAS
N.R.
9.5 mg N/l
0.9 mg P/l
Discharge
1.82 hm3
Reuse
12.03 hm3
15.0 mg N/l
1.5 mg P/l
Vw = 0 hm3
(c)
25.2 mg N/l
3.5 mg P/l
Vr
13.84 hm3
CAS
AnMBR
N.R.
9.5 mg N/l
0.6 mg P/l
Discharge
1.82 hm3
9.14 hm3
Reuse
12.03 hm3
21.4 mg N/l
2.7 mg P/l
Vw = 0 hm3
(d)
25.2 mg N/l
3.5 mg P/l
Vr
13.84 hm3
CAS
N.R.
Discharge
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Vw = 0 hm3

Figure 5

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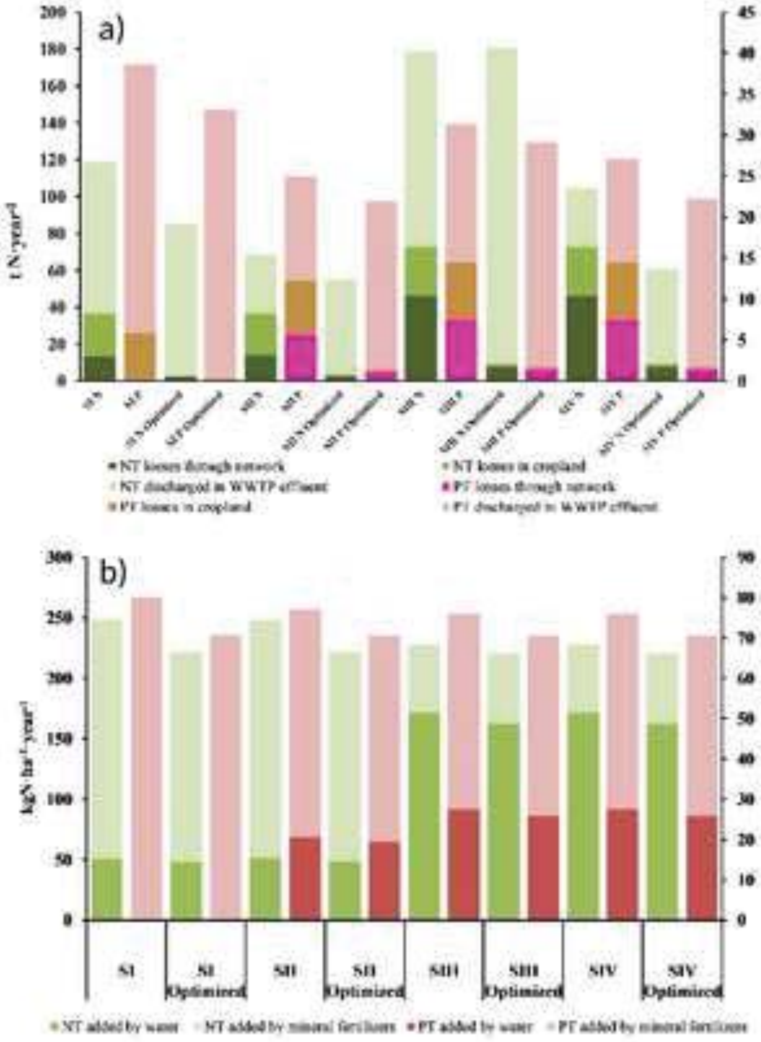

Figure 6
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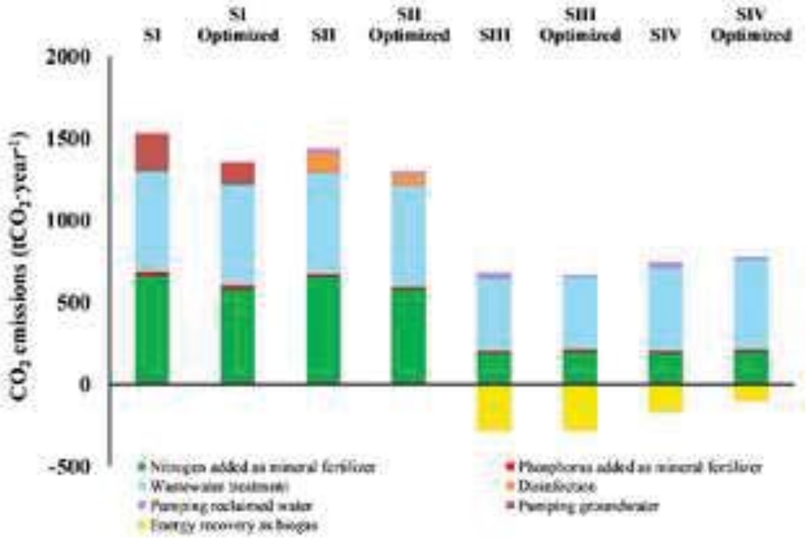

Figure 7

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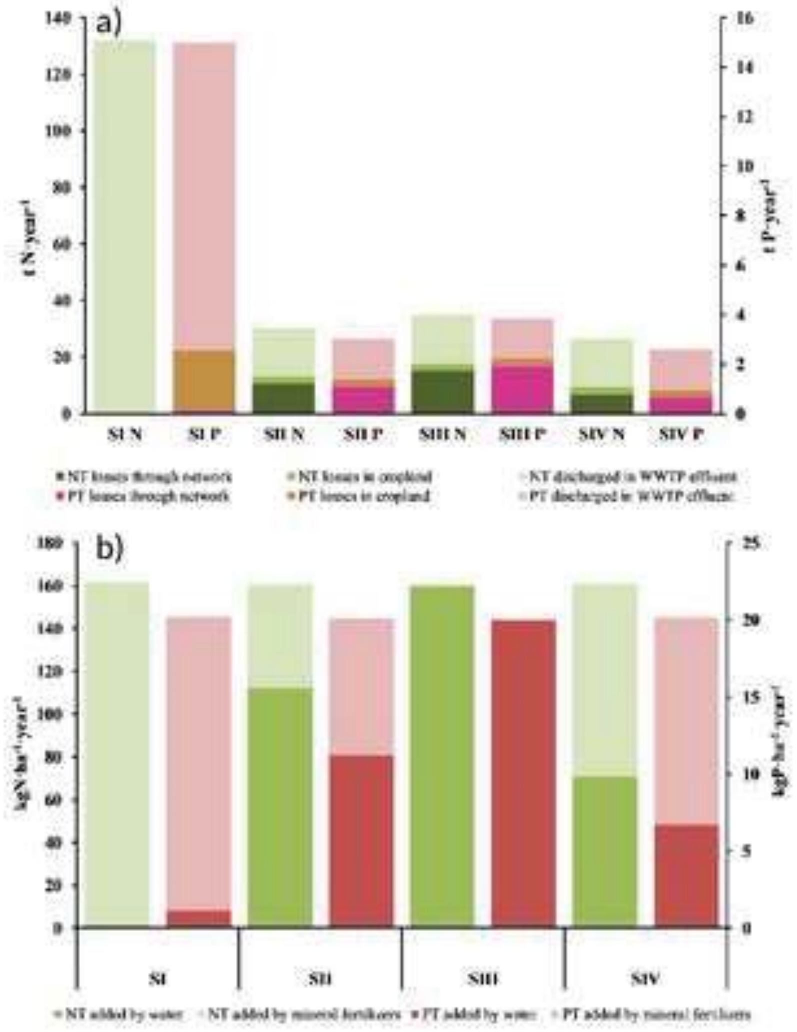

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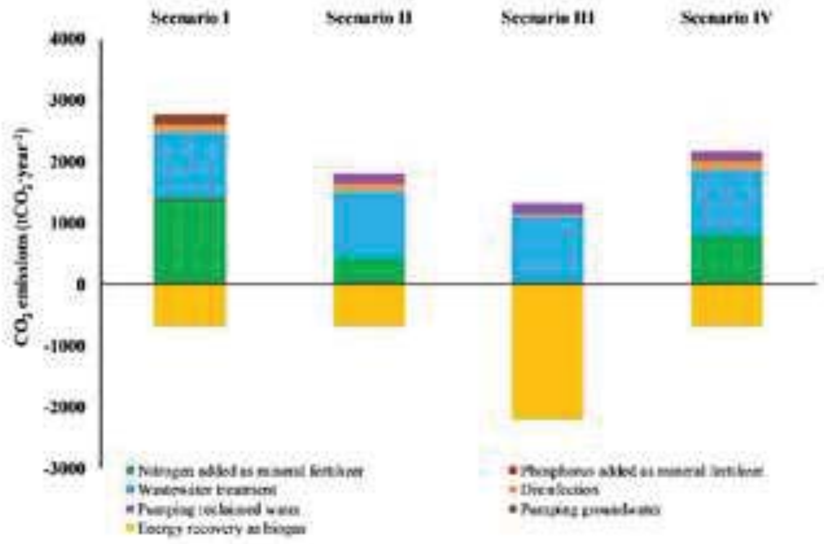

Table 1

Table 1. Cost of most usual mineral fertilizers and unitary treatment energy needs and energy reuse of WWT

Mineral Fertilizer	**Cost (€·kg^{-1})**
Complex 39N-11P-0K	0.39
Urea 46N-0P-0K	0.31
DURAMON 26N-46P-0K	0.32
Lime superphosphate 0N-20P-0K	0.15
Complex 12N-61P-0K	0.66

	Units	**Extended aeration (includes nitrogen removal)**	**AnMBR (without N.R.)**	**References**
Wastewater Treatment	kWh·m^{-3}	[0.35-0.42]	0.269	EPSAR (based on Valencian Community average) and Pretel et al., 2013
Additional treatment for disinfection	kWh·m^{-3}	0.036	----	EPSAR (based on Valencian Community average)
Energy recovery	kWh·m^{-3}	----	[0.12-0.24]	Pretel et al., 2016
Pumping from WWTP	kWh·m^{-3}·h^{-1}	0.004	0.004	EPSAR (based on Valencian Community average)

Table 2

Table 2. Return flows and supplied water efficiency for both Oliva and Peschiera Borromeo case studies.

Irrigation system	(%)	Oliva(1)	Peschiera Borromeo(2)
Transport network	Water loss by evaporation (p_t)	0.3	0.0
	Water loss through return flow (r_t)	14.7	3.0
	Efficiency (e_t)	85.0	97.0
Distribution network	Water loss by evaporation (p_d)	0.0	0.0
	Water loss through return flow (r_d)	15.0	3.0
	Efficiency (e_d)	85.0	97.0
Irrigation method	Water loss by evaporation (p_a)	8.1	2.0
	Water loss through return flow (r_a)	16.5	1.0
	Efficiency (e_a)	75.4	97.0

(1) Percentages calculated from the data supplied by OPH of CHJ.

(2) Percentages calculated for a pipeline network.

Table 3

Table 3. Economic results from the 4 scenarios studied in Oliva WWTP

Costs	Units	SI	SI opt	SII	SIIopt	SIII	SIIIopt	SIV	SIVopt
Wastewater treatment C_{WWT}	k€·year^{-1}	257.0	257.0	257.0	257.0	93.9	93.9	156.8	195.7
Discharge fee $C_{Discharged\ fee}$	k€·year^{-1}	21.9	21.9	8.5	13.7	8.5	13.7	8.5	13.7
WWTP cost	k€·year^{-1}	*278.9*	*278.9*	*265.5*	*270.7*	*102.4*	*107.6*	*165.3*	*209.4*
Extra treatment for reuse $C_{rteat\_for\_reuse}$ (4)	k€·year^{-1}	0.0	0.0	15.0	9.0	0.0	0.0	0.0	0.0
Pumping for reuse $C_{Pumping\text{-}WWT}$ (3)	k€·year^{-1}	0.0	0.0	16.0	9.7	16.0	9.7	16.0	9.7
WWTP + RWTP cost	k€·year^{-1}	*278.9*	*278.9*	*296.5*	*289.4*	*118.4*	*117.3*	*181.3*	*219.1*
Fertilisers $C_{Fertilizers}$	k€·year^{-1}	92.0	81.1	87.0	77.2	31.0	31.1	31.0	31.1
Pumping groundwater $C_{Pumping}$	k€·year^{-1}	110.0	67.3	0.0	0.0	0.0	0.0	0.0	0.0
Farming cost	k€·year^{-1}	*202.0*	*148.4*	*87.0*	*77.2*	*31.0*	*31.1*	*31.0*	*31.1*
Total C_{Total}	k€·year^{-1}	**480.9**	**427.3**	**383.5**	**366.6**	**149.4**	**148.4**	**212.3**	**250.2**
Flow WWTP to manager (2)	k€·year^{-1}	0	0.0	13.4	8.2	176.6	171.3	113.7	69.5
Flow farmer to manager (5)	k€·year^{-1}	0	0.0	115.0	71.2	171.0	117.4	171.0	117.4
RWM Balance	k€·year^{-1}	0	0.0	97.4	60.5	331.6	279.0	268.7	177.1

Table 4

Table 4. Economic results from the 4 scenarios studied in Peschiera Borromeo WWTP

Costs	Units	Scenario I	Scenario II	Scenario III	Scenario IV
Wastewater treatment C_{WWT}	k€·year^{-1}	407.0	407.0	261.0	407.0
Disinfection $C_{Disinfection}$	k€·year^{-1}	69.8	69.8	23.7	69.8
Chemical precipitation	k€·year^{-1}	36.1	4.7	22.6	36.1
WWTP cost	k€·year^{-1}	*512.9*	*481.5*	*307.3*	*512.9*
Pumping for reuse $C_{Pumping\text{-}WWT}$	k€·year^{-1}	0.0	80.8	80.8	80.8
RWTP cost	k€·year^{-1}	*512.9*	*562.3*	*388.1*	*593.7*
Fertilisers $C_{Fertilizers}$	k€·year^{-1}	170.8	53.2	0.0	97.3
Pumping surface water $C_{Pumping}$	k€·year^{-1}	80.8	0.0	0.0	0.0
Farming cost	k€·year^{-1}	*251.6*	*53.2*	*0.0*	*97.3*
Total C_{Total}	k€·year^{-1}	**764.5**	**615.5**	**388.1**	**691.0**
Flow WWTP to manager	k€·year^{-1}	0.0	31.4	205.6	0.0
Flow farmer to manager	k€·year^{-1}	0.0	198.5	251.7	154.4
RWM Balance	k€·year^{-1}	0.0	149.0	376.4	73.6