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AnMBR, reclaimed water and fertigation: two case studies in Italy and Spain to assess economic and technological feasibility and CO_2 emissions within the EU Innovation Deal Initiative

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Abstract

The use of anaerobic membrane bioreactor (AnMBR) technology on urban wastewater can help to alleviate droughts, by reusing the water and nutrients embedded in the effluent in agriculture (fertigation) in line with Circular Economy principles. The combination of

AnMBR and fertigation reduces CO_2 emissions due to the organic matter valorization and the partial avoidance of mineral fertilizer requirements. However, both AnMBR and fertigation still face technological and regulatory barriers that need to be overcome. These bottlenecks were tackled within the first Innovation Deal approved by the European Commission in 2016, and gave rise to several case studies on water reuse systems. The results of the Oliva Wastewater Treatment Plant (Spain) and Peschiera-Borromeo Wastewater Treatment Plant (Italy) showed that reclaimed water can be considered as a reliable water and nutrient source, return a positive economic balance (up to 376 k€·year^{-1}) and provide significant reductions and savings in CO_2 emissions (up to -898.9 $tCO_2\cdot year^{-1}$). According to the new EU regulation, a new key player known as the *Reclaimed Water Manager*, was also proposed to be in charge of supplying reclaimed water with appropriate quantity and quality to end-users. This new agent would also be responsible for drawing up and implementing a Water Reuse Risk Management Plan in cooperation with the parties involved. Applying AnMBR technology to water reuse thus shows potential for contributing to catchment-scale Circular Economy while preserving natural water bodies, reducing the carbon footprint and creating new business opportunities. However, to take full advantage of its benefits demonstration projects would need to be carried out and favorable and harmonized regulations among the EU States would need to be adopted.

Keywords

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

1. Introduction

The worldwide population growth has caused and increasing demand for food and thus greater water extraction and higher consumption of fertilizers (Hussain et al., 2019). According to Ledger et al., (2012) as an additional pressure the current climate change conditions are expected to affect rain patterns and cause water scarcity in many regions. This situation calls for better efficiency in the use of water resources.

In this context, Circular Economy (CE) principles are gaining momentum as part of the solution (Puyol et al., 2017). Their adoption in the water value chain is shifting the conventional wastewater treatment plant (WWTP) model to the water resource recovery facility (WRRF) concept. This can help to achieve economic and environmental goals within the water sector whilst producing valuable goods from a renewable source, including reclaimed water, nutrients, energy, etc.

To promote this paradigm shift, anaerobic membrane bioreactors (AnMBR) have been proposed as potential substitutes for conventional WWTPs, which are generally based on aerobic processes. AnMBR technology combines the advantages of membrane filtration with those of anaerobic processes: effluent quality, organic matter valorization, reduced carbon footprint, low biosolids production and on-site stabilization and nutrients recovery potential. AnMBR applications for industrial wastewater are already well-established (Dereli et al., 2012) and promising results for urban wastewater treatment have been reported: Giménez et al., (2011) showed almost 90 % COD removal and a negligible fouling rate when operating a submerged pilot-scale anaerobic membrane bioreactor with a 10 LMH transmembrane flux and 22 $g \cdot L^{-1}$ suspended solids in the reactor treating real urban wastewater; Ozgun et al., (2013) reported on the membranes' contribution to maintaining high treatment efficiency despite temperature fluctuations due to the retention of particulate COD and biomass in the reactor; Foglia et al., (2019) demonstrated the ability of a combination of UASB and AnMBR to treat high-salinity low-loaded municipal wastewater in the long term with a reduced methane production but without membrane fouling and producing a high-quality effluent, whereas Pretel et al., (2016b) compared different aerobic-based WWTP to AnMBR coupled to a post-treatment for nutrient removal, observing that AnMBR combined with a conventional activated (CAS) sludge-based post-treatment reduced the environmental impact; finally, Becker et al., (2017) showed AnMBR's energy recovery potential when treating joint wastewater and food waste.

However, some issues still need to be addressed in order to improve AnMBR technical, economic and environmental feasibility: the sensitivity and control of process dynamics have been pointed out by Robles et al., (2018); Velasco et al., (2018) focused on the release of dissolved methane with the effluent; several authors (e.g. Aslam et al., 2018; Judd, 2017; Maaz et al., 2019) coincide in considering membrane fouling as one of the major bottlenecks; and Smith et al., (2012) underlined eutrophication potential due to the nutrients content of its effluent. However, it is precisely the presence of N and P in the

AnMBR effluent, together with the high quality of the water, that makes their application for fertigation an attractive approach for resource recovery.

Fertigation (simultaneous reuse of water and nutrients) helps to conserve freshwater sources and reduces the energy consumed for industrial ammonia-based fertilizer production (19.3 kWh·kg N^{-1} by the Haber-Bosh process, according to McCarty et al., 2011) and P extraction (2.11 kWh·kg P^{-1} according to Gellings and Parmenter, 2004). Financial benefits for farmers can also be expected from savings in mineral fertilizers (Scheierling et al., 2011). P was included in the EU's Critical Raw Materials list in 2017 (European Commission, 2017), which justifies strategies for reducing European dependency on nutrient importation from a food security perspective as well as from an environmental point of view.

Several documents, regulation proposals, reports and scientific papers have been published on the benefits of water reclamation and its related issues (Alcalde-Sanz and Gawlik, 2017; General Secretariat of the Council, 2019; WWAP, 2017). As stated by Condom et al., (2012), the main challenges are not only technological, environmental and economic: social acceptance and the political framework are also crucial and therefore need to be properly considered in order to guarantee feasibility and sustainability of water reuse projects and plans The EU has already recognized that the use of reclaimed water has a smaller environmental impact than other alternatives, i.e. water transfers or desalination, while it also has financial and social benefits (European Commission-DG ENV, 2012). The main current concerns are related to microbial risks to public health and the environment risks. These are generally addressed by a multibarrier approach in wastewater treatment/reclamation and the development and implementation of water reuse risk management plans (WRRMP).

Based on this background, and with the aim of investigating whether the AnMBR technology for reclaiming water for fertigation faces regulatory barriers in the EU, the European Commission (EC) approved the first pilot Innovation Deal (ID) entitled *Sustainable wastewater treatment combining anaerobic membrane technology and water reuse* in 2016. The ID consortium consisted of 14 partners from 5 European member states (Portugal, Spain, Malta, Italy and France) and included a comprehensive group of stakeholders involved in water management: national and regional authorities, universities, research centers, innovators and end-users. Three EC Directorate-Generals (Research and Innovation, Agriculture and Rural Development and Environment) were also represented.

The tasks carried out within the ID included the analysis of several case studies, two of which are presented in this study. These cases are located in the Mediterranean Region (Italy and Spain) and compare the application of combined AnMBR technology and fertigation with conventional configurations of WWTPs with aerobic systems, irrigation with freshwater and mineral fertilization. To the best of authors' knowledge, this has not been reported on before. The work carried out also included the development of the novel concept of the Reclaimed Water Manager (RWM), a new key player in accordance with the EU regulation, who will be in charge of operating water reclamation and reuse systems and responsible for drawing up and applying the WRRMP. Both case studies examined different scenarios and compared them to the current case. An economic study was performed for the RWM and the levels of wastewater resource recovery and CO_2 emissions were assessed for all configurations.

2. Material and Methods

Each case study encompassed different scenarios in which at least one was AnMBR technology. A four-step assessment methodology was developed to analyze them: (i) water balance, (ii) nutrient balance, (iii) economic analysis and (iv) CO_2 emission estimations. Several reference values were used (see below in this section), based on the literature and on data provided by stakeholders (e.g. efficiency factors, water and nutrients needs, energy needs, energy prices, etc.). Further studies must find the most appropriate variables for each specific case in order to increase the accuracy of the results. Information on the end-users' perception on water reuse for agriculture was also gathered and analyzed.

2.1. Water balance

In the first step, the *net crop requirements* or *net provision* ($m^3 \cdot ha^{-1} \cdot year^{-1}$) is calculated, considering 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. The second step is a water balance 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 throughout the irrigation network: evaporation in the transport network (p_t), in the distribution network (p_d) and 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:

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

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

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

where V_D ($hm^3 \cdot year^{-1}$) is the irrigation influent water volume to the distribution network, V_P ($hm^3 \cdot year^{-1}$) is the volume applied to cropland and V_N ($hm^3 \cdot year^{-1}$) is the net irrigation volume.

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

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

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

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

2.2. Nutrient balance

During the nutrient balance step, the total amount of nutrients in the irrigation water is calculated together with the complementary mineral fertilizers needed to fully provide the crops with the optimal nutrients supply. The balance also evaluates the total amount of nutrients released into water bodies and is applied taking into account that water losses by evaporation give rise to higher nutrient concentrations throughout the water network (Eq. 7, Figure 1).

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

where C represents nutrient concentration (N or P), F is the fertilizer surplus, r is the return flow. Subscripts B, t, d and a indicate the water flow section in which 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) encompasses 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).

Other agronomic considerations, e.g. micronutrients, soil quality, etc., which could change crop nutrient uptakes were outside the scope of this study.

2.3. Economic balance

Figure 2 shows the different water, nutrient and money flows in a water re-use system to which the economic balance was applied to evaluate the feasibility of AnMBR for fertigation. As proposed by the authors and in line with the new EU regulation proposal (General Secretariat of the Council, 2019), the Reclaimed Water Manager was included. The RWM is the managing body responsible for operating, controlling and supervising the re-use system and would be in charge of drafting and implementing the Water Reuse Risk Management Plan in collaboration with the relevant parties.

Figure 2. Water (full line), nutrients (dotted line) and money 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 sewer system. Based on the "*polluter pays principle*", there is a parallel money (tax/tariff) flow from the users (polluters) to the WWTP.

- Treated water and 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.
- According to the crop requirements, farmers might need to add mineral industrial fertilizers, which creates a money flow to fertilizer producers. If enough nutrients are present in the reclaimed water, this money flow can be reduced or even disappear.
- The farmers would pay the RWM for controlling the water re-use system and providing enough good-quality water. This opens a new market niche and business opportunity. The RWM would 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 re-use, 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:

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

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 re-use) 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. Since the purchase of mineral fertilizer was partially or totally avoided, the RWM could profit from the associated savings.

2.3.1. Unit costs and energy consumption

Commercial fertilizer prices and energy consumption in Spain was estimated as shown in Table 1, assuming a WWTP energy cost of 0.125 $€\cdot kWh^{-1}$. Energy consumption of 0.26 $kWh\cdot m^{-3}$ 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 $€\cdot kWh^{-1}$. Costs of 4.35 $€\cdot kgP_{removed}^{-1}$ 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 $€\cdot m^{-3}$ for chemical membrane cleaning related to AnMBR technology (Pretel et al., 2016a). A pumping energy cost of 0.137 $€\cdot kWh^{-1}$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 (data provided by Júcar River Basin Authority and Regional Government of Valencia). (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.

2.4. 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-related CO_2 emissions were based on the energy consumption given in Section 2.4. considering a European average electricity specific emission factor of 0.2958 kg CO_2·kWh^{-1} (EEA, 2018). The energy required for fertilizer production was assumed to be 19.3 kWh·kg N^{-1} by the Haber-Bosh Process (McCarty et al., 2011) and 2.11 kWh·kg P^{-1} (Gellings and Parmenter, 2004)

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

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

2.5. End-users' perception

One of the social bottlenecks in agricultural water reuse identified in the Innovation Deal is the lack of current knowledge on the public perception and social acceptance of the reuse concept. A survey was therefore carried out to collect the end-users' feedback. 15 irrigators from the Mediterranean coast in Spain (Catalonia, Valencia, Alicante and Murcia) and one from Murviel Lès Montpellier in France collaborated in the survey and responded to questions related to crops, water use, water source, water quality, economics of water reuse, water supply problems and their attitude to using reclaimed wastewater for their crops.

2.6. Case studies description

The ID consortium carried out four case studies as part of the tasks involved in the project. This paper presents only the representative cases of Oliva (Spain) and Peschiera-

Borromeo (Italy) WWTPs, as they could be replicated in many similar sites in both European countries, where the proposed technology could enhance agriculture sustainability with water reclamation and nutrient recovery and re-use.

2.6.1. Oliva WWTP

With a WWT flow (V_T) of 5.5 hm^3·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·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.

2.6.1.1. 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 m^3·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·ha^{-1}·year^{-1} and 80 kg P·ha^{-1}·year^{-1} for flood irrigation and 220 kg N·ha^{-1}·year^{-1} and 70 kg P·ha^{-1}·year^{-1} for drip irrigation (López Bellido et al., 2010; Valencian Ministry of Agriculture; Environment; Climate Change and Rural Development, 2018).

2.6.1.2. 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 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·m^{-3} (Table 1). In the case of the Oliva WWTP, a value of 0.375 kWh·m^{-3} was considered due to the treatment flow and the extent of N removal. Although SI meets the UWWTD requirements, it is still far from complying with the CE objectives, since water, energy and nutrients are not re-used. Fertigation could be used for agricultural water and nutrient demands, as shown in Scenarios II, III and IV (Figure 3.), in which 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 $mg·L^{-1}$, respectively. In SIII it is assumed that 100 % of WWTP inflow is treated with AnMBR technology instead of EA, providing a nutrient-rich effluent with concentrations similar to the usual values in WWTPs influent (50 $mg\ N·L^{-1}$ and 8 $mg\ P·L^{-1}$ according to EPSAR) and biogas generated by anaerobic digestion of organic matter in wastewater. Although the Oliva WWTP discharges into a non-sensitive area, an SIV was evaluated (Figure 3.) in which wastewater is treated by two parallel lines (AnMBR and EA) to reduce the 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

The Peschiera Borromeo WWTP is currently treating an average inflow rate of 78.84 $hm^3·year^{-1}$ (566,000 p.e.) by two water lines that receive wastewater from the Milan metropolitan area. Line 1 consists of a CAS process followed by tertiary treatment (disinfection with peracetic acid) while line 2 consists of an upflow biological filtration for nutrient removal and UV disinfection. This WWTP is situated in the municipality of Peschiera Borromeo (Lombardy, Italy) and discharged into the Lambro River, which was declared a sensitive area by the UWWTD and a vulnerable zone by the NiD. It should be noted that the Italian regulations set the total nitrogen (N_T) and total phosphorus (P_T) standard for water re-use at 15 and 2 $mg·L^{-1}$, respectively, so that the WWTPs must remove the nutrients before water reclamation. This is one of the major economic barriers to possible fertigation and in this case study the polluter price includes the cost of chemical precipitation and disinfection.

2.6.2.1. Water and nutrients needs

The surrounding agricultural land which could potentially be irrigated with reclaimed water has an extension of 1,500 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 the WWTP's water line 2. This plant is in a peri-urban agricultural park (Parco Agricolo Sud Milano) whose main crop is tomatoes. The average water requirements are 7.318 $m^3·ha^{-1}$ from April to September (183 days). Tomato N and P needs for drip irrigation systems are 160 $kg\ N·ha^{-}$

$^{1}\cdot$year^{-1} and 20 kg P$\cdot$ha$^{-1}\cdot$year^{-1} (Valencian Ministry of Agriculture; Environment; Climate Change and Rural Development, 2018).

2.6.2.2.Analyzed scenarios

The scenarios studied in the Peschiera Borromeo WWTP are depicted in Figure 4. 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, affecting both the resource and the surrounding ecosystem. Although a large amount of energy is required for WWT, SI is the common situation in many parts of Italy due to the restrictive legislation, 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 bypass 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 through biogas production, while generating a nutrient-rich effluent that would notably reduce fertilizer costs. In this scenario and in SII, a modification of the Italian regulations is assumed to allow either land application as a wastewater post-treatment, or the use of reclaimed water as a fertilizer product.

In SIV all wastewater is treated through a CAS system with nutrient removal and water is re-used for agriculture. SIV represents the current situation of some Italian WWTPs, such as Milano San Rocco and Milano Nosedo, where farmers supply part of the effluent for irrigation together with their own artificial fertilizers.

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

3. Results and discussion

This section presents and discusses the main results obtained for the two case studies analyzed.

3.1. Efficiency factors

Preliminary studies (not shown) 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 distribution 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 is 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 Scenarios II and III, 61.3 % of the wastewater treated in the Oliva WWTP is reused.

A total supplied water efficiency of 54.5 % was calculated (Table 2), showing that there are high water losses throughout the irrigation network due to the return flows and the irrigation method used (flooding). 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 increase in network efficiency.

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

3.2.2. Nutrient balance

Used as the baseline, SI discharges treated wastewater into coastal waters, releasing 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·ha^{-1}·year^{-1}, reducing mineral P addition by 29.4 % (Figure 5a).

The application of AnMBR technology in SIII reduces P losses by 18.9 % (SIII compared to SI, Figure 5a) while N discharged into the environment increases from 118.7 t·year^{-1} in SI to 178.6 t·year^{-1} in SIII. The reason behind this result lies in the fact that the N content in the AnMBR effluent is higher (from 15 to 50 mg·L^{-1}) than for P concentration (from 6 to 8 mg·L^{-1}, Figure 3), so that 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 flow 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 added mineral needs as SIII and reduces nutrient losses with respect to Scenarios I and III.

Figure 5. a) Nutrients discharged into the environment in the four scenarios proposed in Oliva WWTP; b) Results of nutrient balance applied to cropland in the four 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 four 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 shown in Table 3. The operating costs of AnMBR wastewater treatment are 63.4 % lower in SIII and 39 % lower 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. A pumping cost is required in all the scenarios, but groundwater extraction pumping costs disappear in SII to SIV. Fertilizer costs are also reduced due to fertigation, especially when the reclaimed wastewater is obtained from AnMBR.

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

As explained above, the authors propose to maintain the total cost for polluters and farmers in all cases equal to that of SI (278.9 and 202.0 k€·year^{-1}, respectively). A flow from the WWTP to the RWM would be possible in the water re-use scenarios, since WWTP cost would actually be smaller due to lower discharge fees and C_{WWT}. Similarly, due to savings in fertilizers and groundwater pumping, part of the farmers' expenses could be transferred to the RWM, who would have a total income of 0.029 (SII), 0.099 (SIII) and 0.080 (SIV) €·m$^{-3}_{reused}$ (Table 3).

The results show the economic viability of AnMBR technology, since the total cost was reduced from 480.9 k€·year^{-1} (SI) to 149.4 k€·year^{-1} (SIII) or 212.3 k€·year^{-1} (SIV). At the same time, Scenarios III and IV do not only meet the UWWTD and NiD requirements, but also reduce the costs associated with fertilizers and pumping. This means that the RWM budget can be devoted to covering the reclaimed water management expenses (including the WRRMP).

The economic balance for the four scenarios shows that, while the wastewater treatment costs with and without optimized irrigation networks remain constant for Scenarios I to III, discharge fees increase and the available money flow from the WWTP to the RWM is reduced. The same wastewater flow needs to be treated per year but a higher flow of treated water is discharged since a smaller water flow is reclaimed. On the other hand, as the reclaimed water flow is only 61 % of that in the non-optimized scenarios, disinfection and pumping costs and mineral fertilization need to be reduced (Table 3). Water re-use costs are therefore reduced due to the smaller water flow needed by a more efficient system.

In SI, where treated water is not reclaimed, groundwater pumping costs also decreased for the same reason. A lower farmer's price was thus obtained for the optimized scenarios (148.4 k€·year^{-1}) and the following total RWM income reduction was calculated: 37.7 % in SII, 15.9 % in SIII and 34.1 % in SIV. The reasons for this are the downscaled re-use 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 the farmer's price due to the lower cost of optimized SI.

An optimized irrigation system saves water ready for re-use 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. Water re-use 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. An improvement is also observed when comparing Scenarios II to IV, with reclaimed water, to SI, where no water is reclaimed.

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, the CO_2 emissions associated with fertilizer production are reduced by the same proportion. The high energy consumption in the EA process and the absence of energy recovery in this treatment produce higher CO_2 emissions than SIII. This scenario, in which AnMBR is combined with an optimized irrigation system, provided the highest environmental benefit in terms of total CO_2 emissions (reduction of up to 1153 t $CO_2 \cdot year^{-1}$).

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

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.

The positive impact of AnMBR would be still higher, if groundwater conservation could be quantified. Applying this technology in vulnerable zones requires risk assessment plans, including nutrient balances. Methods such as drip irrigation 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 is used for irrigation (Figure 4), depleting natural resources. Fertigation (Scenarios II and III) or irrigation (SIV) would improve the conservation of water bodies. In these scenarios, 87 % of the wastewater treated in the Peschiera Borromeo WWTP would be re-used. The irrigation network in the surrounding area was designed with pipelines and the present irrigation method is by drip, so that the results are those of an optimized irrigation system.

3.3.2. Nutrient balance

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 % (SII), 73.5 % (SIII) and 79.9 % (SIV) 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 four scenarios studied in Peschiera Borromeo WWTP; b) Nutrients balance applied to cropland in the four scenarios studied in Peschiera Borromeo WWTP

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

Since there is no clear advantage regarding nutrient losses for any of the three water re-use scenarios, the economic and CO_2 emissions analyses become decisive.

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. In fact, they are not an additional treatment because, according to the Italian regulations, nutrients must be removed from the final effluent up to the allowed quality standard. 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). Since irrigation water has to be pumped either from surface water bodies or from WWTP effluent, all water scenarios include water pumping costs. Fertilizer costs decrease in the situations with water re-use, being zero when AnMBR technology is applied, which brings considerable savings in farming costs. Water re-use scenarios provide a relevant money flow from farmers to the RWM, especially in Scenarios II and III, due to the higher contribution of the WWTP effluent to fertilization needs.

Table 4. Economic results of the four 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 re-use scenarios. This is a direct consequence of removing all the nutrients from the influent, which means a higher quantity of mineral fertilizers is needed. This, in turn, results in fewer 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 re-use system to 388.1 k€·year^{-1} due to the following factors: (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 and the reduced disinfection and chemical precipitation costs.

3.3.4. Carbon dioxide emissions

Figure 8. CO_2 emissions for the four 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 re-use with CAS treatment (SII) reduced CO_2 emissions by 46.4 % with respect to the present situation, while the smallest carbon footprint was obtained for SIII, with AnMBR technology (-898.9 $tCO_2 \cdot year^{-1}$). On the one hand, the possible energy recovery as biogas is substantially higher with this wastewater treatment than with CAS, while on the other the avoidance of mineral fertilizers also prevented a major CO_2 emissions source. These results show that the AnMBR/fertigation combination can considerably reduce the carbon footprint and the financial costs 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.

3.4. End-user acceptance

The survey was disseminated among irrigators whose average annual water usage is 5000 m^3/ha. The responses revealed that 87.5% of those surveyed have at some point if not currently irrigated their crops with reclaimed water and 64% of these cases declared that they achieved an economic benefit in doing so. The study showed that scarcity problems are more frequent or are more important to the farmers surveyed than water quality problems. Finally, one of the main results of this study was that all (100%) the irrigators surveyed claimed that they would be willing to use water from a wastewater treatment plant if they could be sure it is of high quality, which is consistent with their acknowledgement that reclaimed water guarantees the water supply.

4. Conclusions

Reclaimed water is a reliable resource that can be associated with a relevant renewable nutrient supply. It is independent of seasonal droughts and weather variations and thus acts as an alternative resource to alleviate pressure on freshwater sources, while reducing the economic and environmental costs of mineral fertilizers. However, a risk management plan is needed to ensure environmental and health safety when reclaimed water is used for both irrigation and fertigation.

This work has shown the positive economic balance that can be obtained in different water reuse scenarios. The authors propose that savings can be used for drawing up, updating and implementing the Water Re-use Risk Management Plans under the responsibility of the new *Reclaimed Water Manager*.

Since AnMBR technology can also recover energy from the wastewater flow, its application presents an optimal scenario according to Circular Economy principles and environmental sustainability. In this regard, the combination of AnMBR technology and fertigation can significantly reduce CO_2 emissions.

Lastly, in order to comply with the current legislation, future combined AnMBR and fertigation demonstration projects need to be carried out in non-sensitive areas, following the ID conclusions. These trials should include environmental and health risk assessments, agronomic studies and social and economic analyses to obtain comprehensive information of the proposed water management scheme.

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Table Legends

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

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

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

Table 4. Economic results from the four 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 money 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

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

Figure 5. a) Nutrients discharged into the environment in the four scenarios studied in Oliva WWTP; b) Nutrient balance applied to cropland in the four scenarios studied in Oliva WWTP

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

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

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

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., 2016b
Pumping from WWTP	kWh·m^{-3}·h^{-1}	0.004	0.004	EPSAR (based on Valencian Community average)

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.

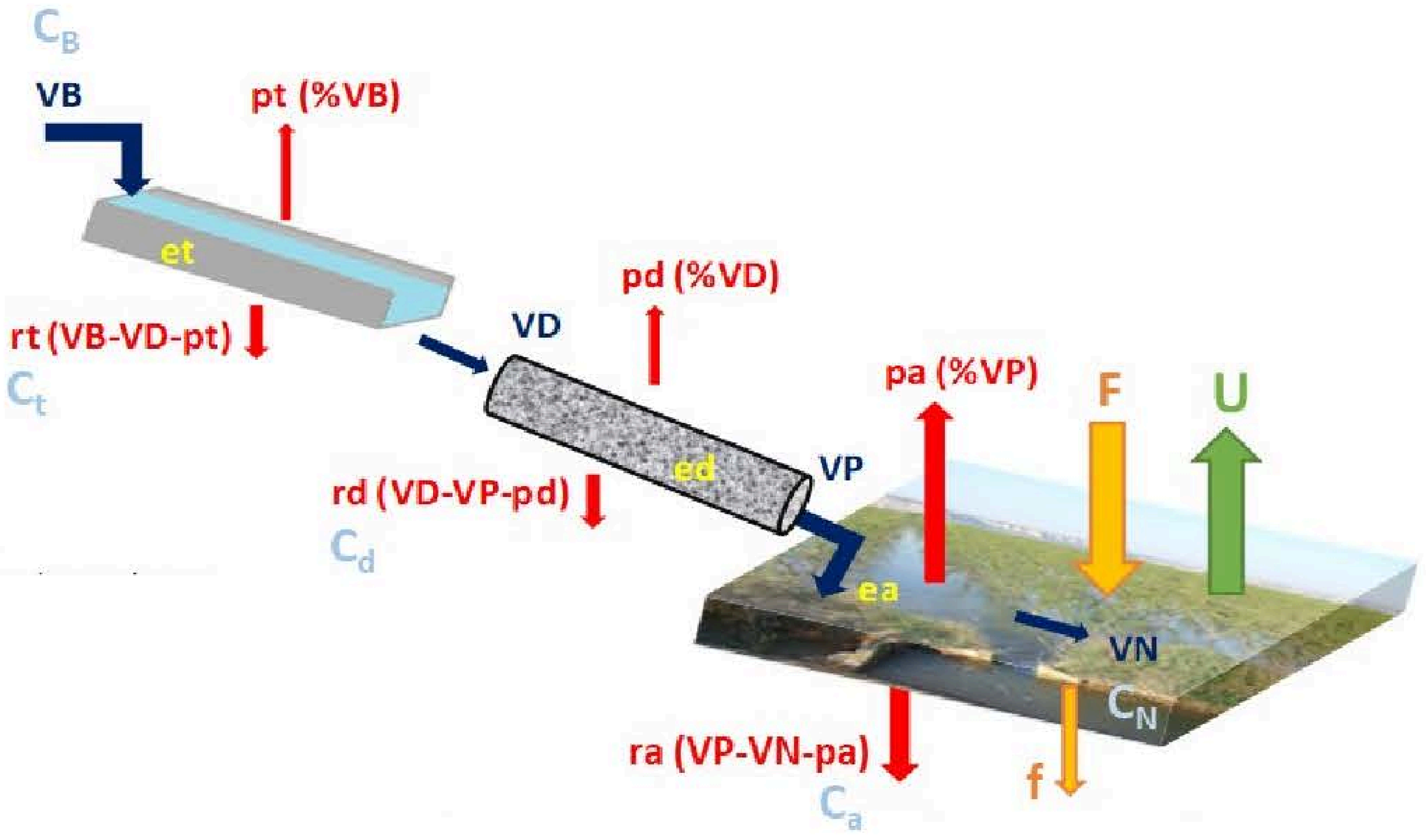
(2) Percentages calculated for a pipeline network.

Table 3. 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 $C_{Pumping-WWT}$ (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. 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 $C_{Pumping-WWT}$	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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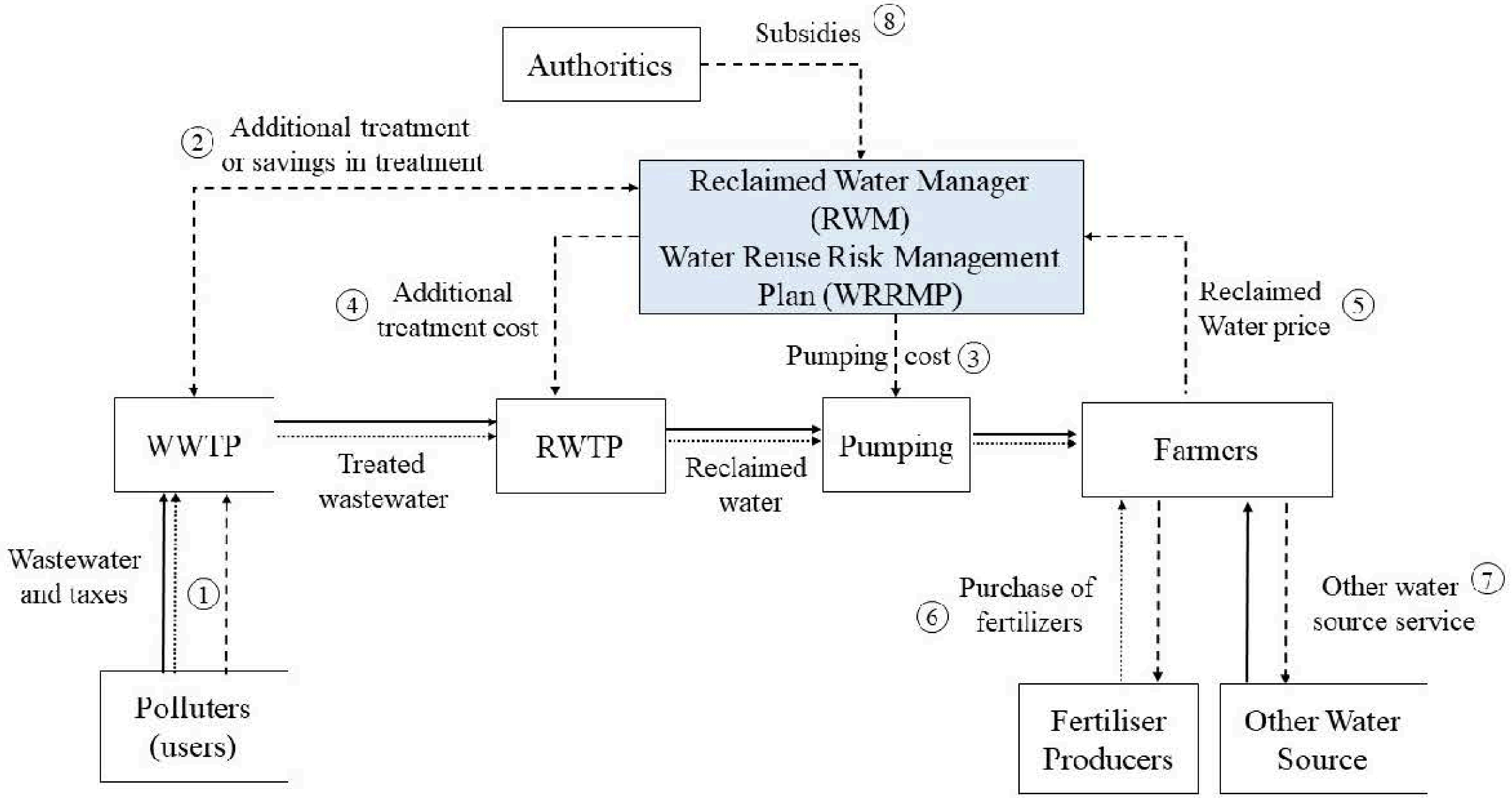
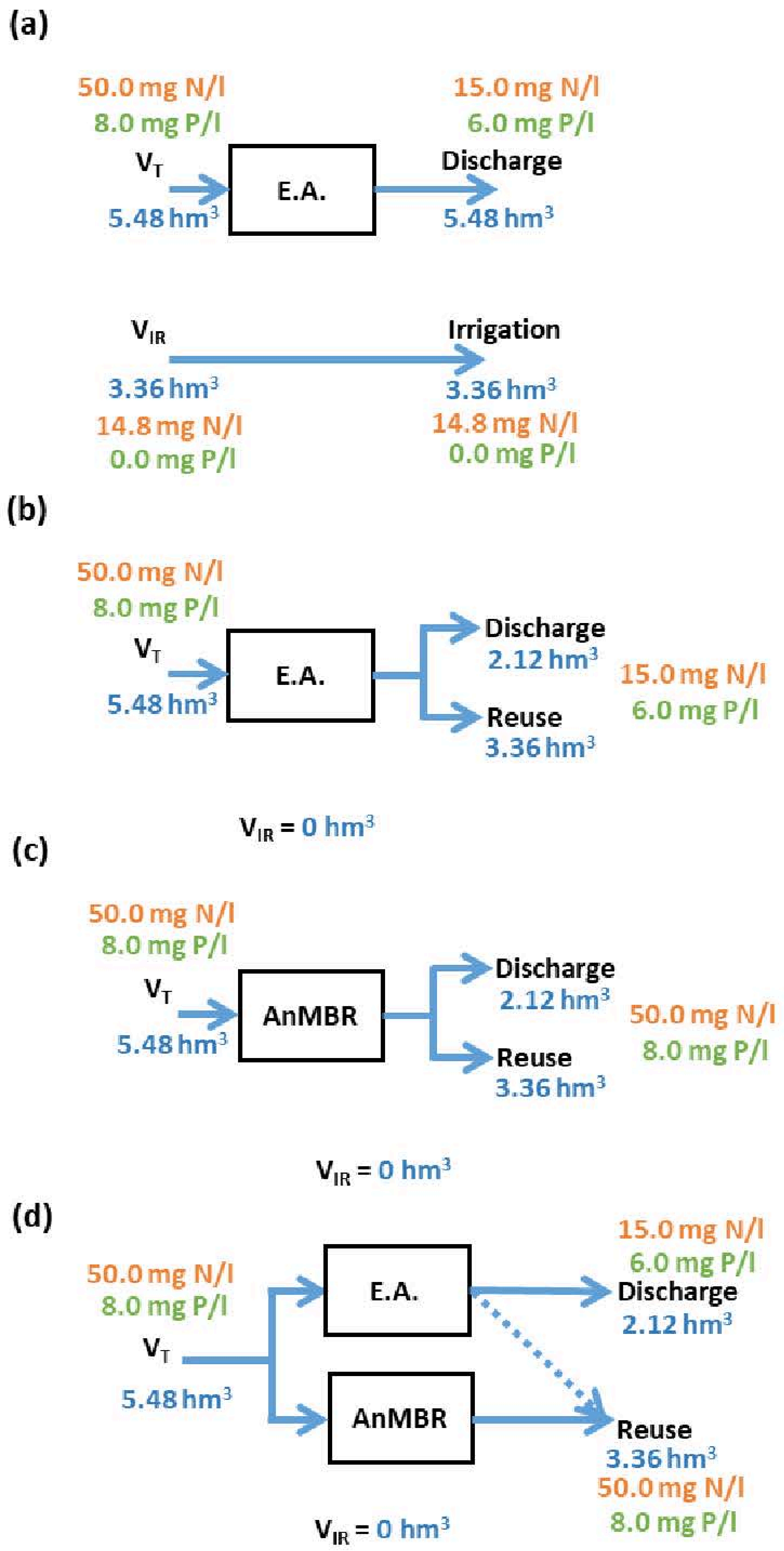
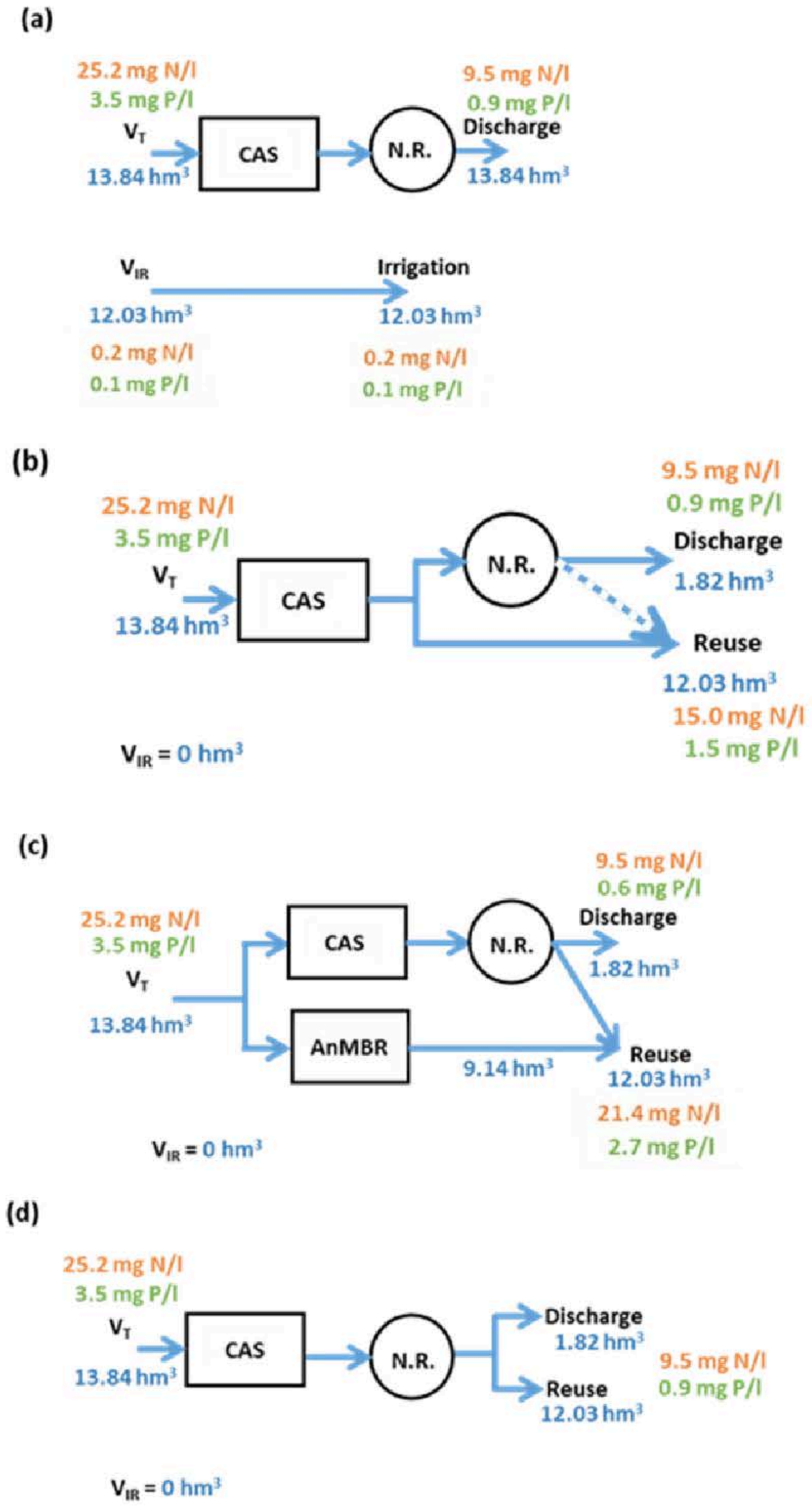
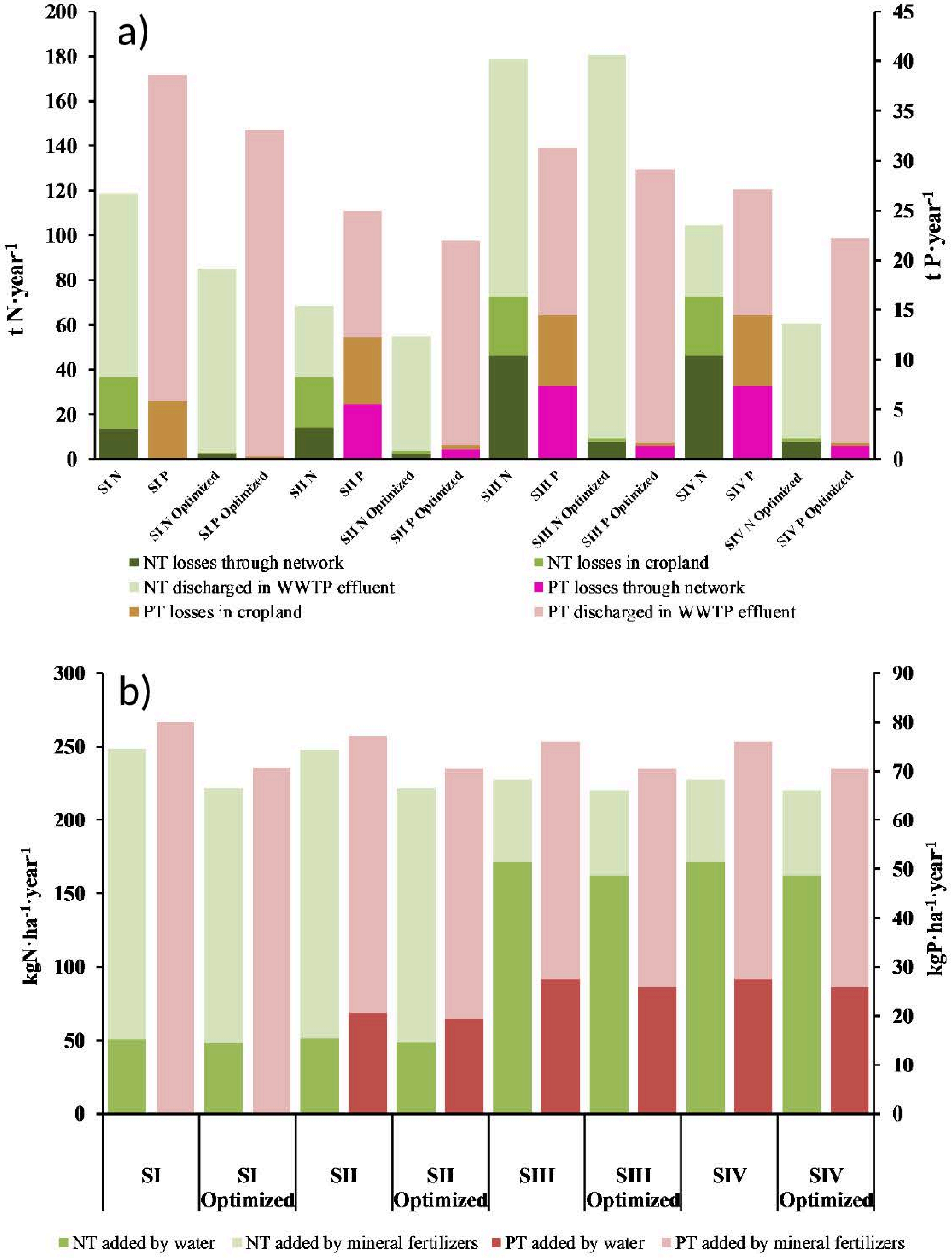
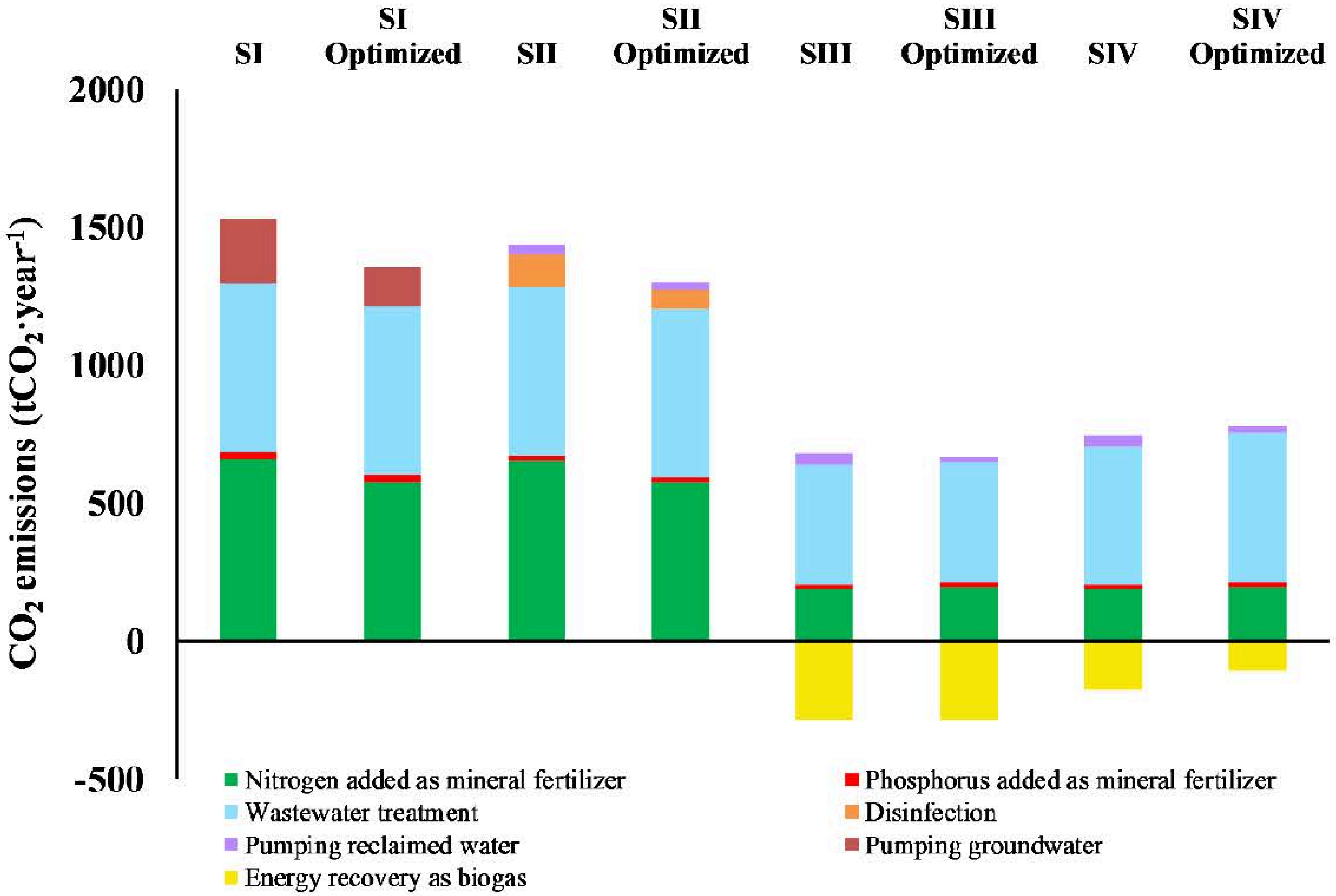
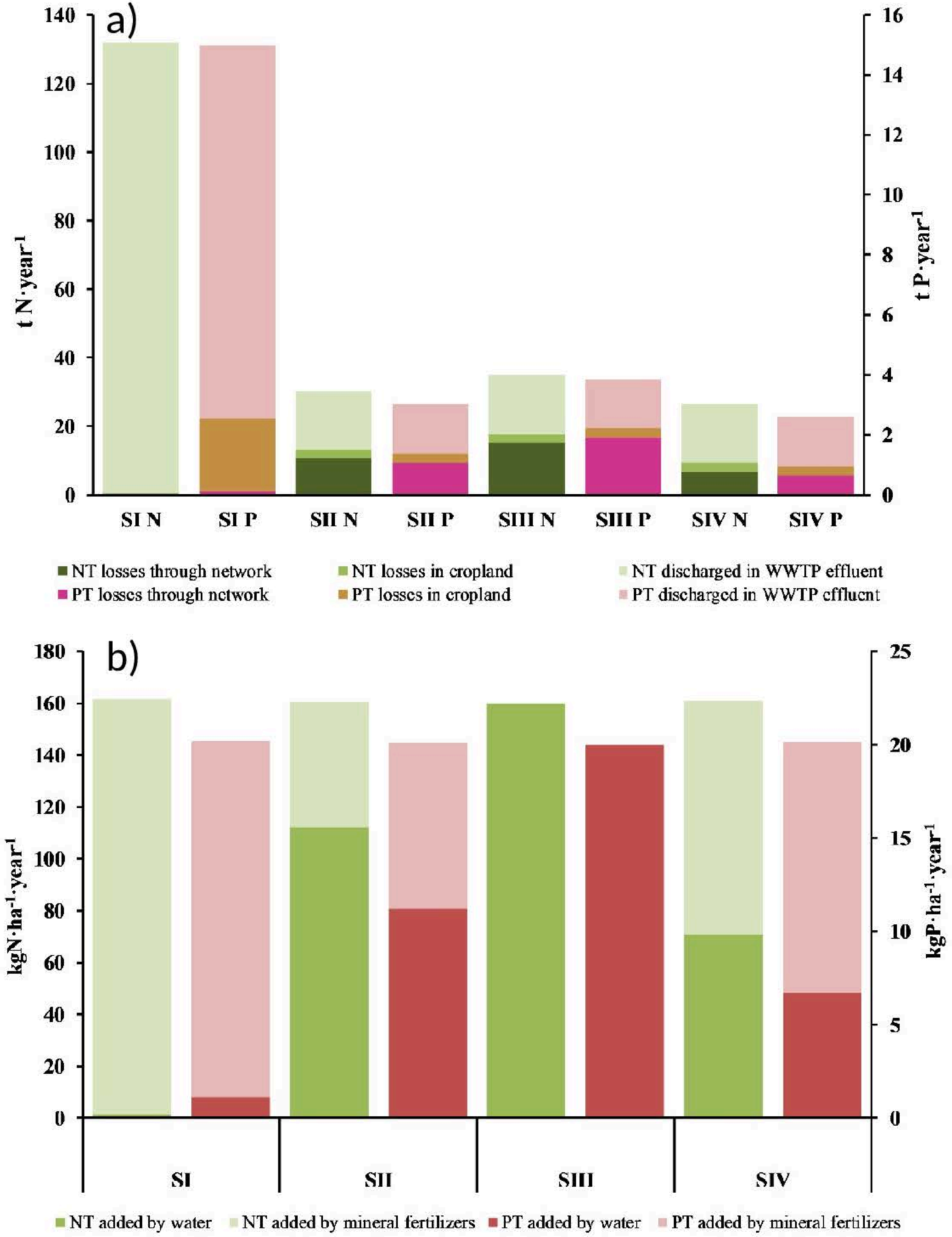

Authorities
Subsidies ⑧
② Additional treatment or savings in treatment
Reclaimed Water Manager (RWM)
Water Reuse Risk Management Plan (WRRMP)
④ Additional treatment cost
Reclaimed Water price ⑤
Pumping cost ③
WWTP
Treated wastewater
RWTP
Reclaimed water
Pumping
Farmers
Wastewater and taxes
①
Polluters (users)
⑥ Purchase of fertilizers
Other water source service ⑦
Fertiliser Producers
Other Water Source

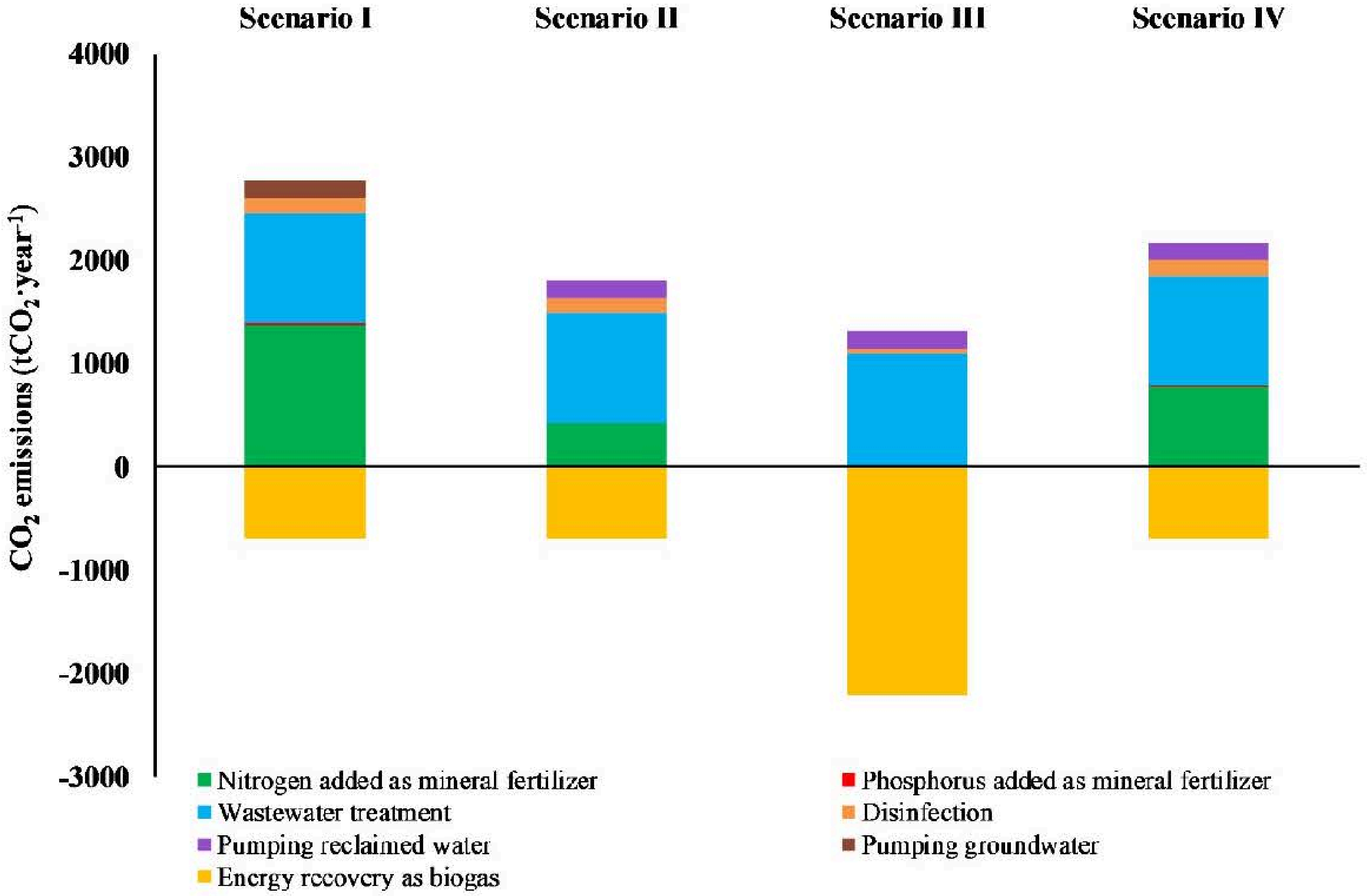

(a)
50.0 mg N/l
8.0 mg P/l
V_T
5.48 hm^3
E.A.
15.0 mg N/l
6.0 mg P/l
Discharge
5.48 hm^3
V_{IR}
Irrigation
3.36 hm^3
14.8 mg N/l
0.0 mg P/l
3.36 hm^3
14.8 mg N/l
0.0 mg P/l
(b)
50.0 mg N/l
8.0 mg P/l
V_T
5.48 hm^3
E.A.
Discharge
2.12 hm^3
Reuse
3.36 hm^3
15.0 mg N/l
6.0 mg P/l
V_{IR} = 0 hm^3
(c)
50.0 mg N/l
8.0 mg P/l
V_T
5.48 hm^3
AnMBR
Discharge
2.12 hm^3
Reuse
3.36 hm^3
50.0 mg N/l
8.0 mg P/l
V_{IR} = 0 hm^3
(d)
50.0 mg N/l
8.0 mg P/l
V_T
5.48 hm^3
E.A.
AnMBR
15.0 mg N/l
6.0 mg P/l
Discharge
2.12 hm^3
Reuse
3.36 hm^3
50.0 mg N/l
8.0 mg P/l
V_{IR} = 0 hm^3


(a)
25.2 mg N/l
3.5 mg P/l
V_T
13.84 hm³
CAS
N.R.
9.5 mg N/l
0.9 mg P/l
Discharge
13.84 hm³
V_{IR}
Irrigation
12.03 hm³
12.03 hm³
0.2 mg N/l
0.1 mg P/l
0.2 mg N/l
0.1 mg P/l
(b)
25.2 mg N/l
3.5 mg P/l
V_T
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
V_{IR} = 0 hm³
(c)
25.2 mg N/l
3.5 mg P/l
V_T
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
V_{IR} = 0 hm³
(d)
25.2 mg N/l
3.5 mg P/l
V_T
13.84 hm³
CAS
N.R.
Discharge
1.82 hm³
Reuse
12.03 hm³
9.5 mg N/l
0.9 mg P/l
V_{IR} = 0 hm³


a)
t N·year^{-1}
t P·year^{-1}
0
20
40
60
80
100
120
140
160
180
200
0
5
10
15
20
25
30
35
40
45
SI N
SI P
SI N Optimized
SI P Optimized
SII N
SII P
SII N Optimized
SII P Optimized
SIII N
SIII P
SIII N Optimized
SIII P Optimized
SIV N
SIV P
SIV N Optimized
SIV P Optimized
NT losses through network
NT losses in cropland
NT discharged in WWTP effluent
PT losses through network
PT losses in cropland
PT discharged in WWTP effluent
b)
kgN·ha^{-1}·year^{-1}
kgP·ha^{-1}·year^{-1}
0
50
100
150
200
250
300
0
10
20
30
40
50
60
70
80
90
SI
SI Optimized
SII
SII Optimized
SIII
SIII Optimized
SIV
SIV Optimized
NT added by water
NT added by mineral fertilizers
PT added by water
PT added by mineral fertilizers


SI
SI Optimized
SII
SII Optimized
SIII
SIII Optimized
SIV
SIV Optimized
2000
1500
1000
500
0
-500
CO$_2$ emissions (tCO$_2$·year^{-1})
Nitrogen added as mineral fertilizer
Phosphorus added as mineral fertilizer
Wastewater treatment
Disinfection
Pumping reclaimed water
Pumping groundwater
Energy recovery as biogas


a)
t N·year-1
t P·year-1
0
20
40
60
80
100
120
140
0
2
4
6
8
10
12
14
16
SI N
SI P
SII N
SII P
SIII N
SIII P
SIV N
SIV P
NT losses through network
NT losses in cropland
NT discharged in WWTP effluent
PT losses through network
PT losses in cropland
PT discharged in WWTP effluent
b)
kgN·ha-1·year-1
kgP·ha-1·year-1
0
20
40
60
80
100
120
140
160
180
0
5
10
15
20
25
SI
SII
SIII
SIV
NT added by water
NT added by mineral fertilizers
PT added by water
PT added by mineral fertilizers


Scenario I
Scenario II
Scenario III
Scenario IV
4000
3000
2000
1000
0
-1000
-2000
-3000
CO_2 emissions ($tCO_2 \cdot year^{-1}$)
Nitrogen added as mineral fertilizer
Phosphorus added as mineral fertilizer
Wastewater treatment
Disinfection
Pumping reclaimed water
Pumping groundwater
Energy recovery as biogas