Feasibility assessment of reclaimed wastewater reuse in agriculture: how we do it

L. Penserini*, A. Moretti**, M. Mainardis**, L. Rizzo***, S. Bozza***, M. Olivieri***, B. Cantoni*, M. Antonelli*

* Department of Civil and Environmental Engineering (DICA) - Environmental Section, Politecnico Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy
(E-mail: *luca.penserini@polimi.it; beatrice.cantoni@polimi.it*; *manuela.antonelli@polimi.it)*
** Università degli studi di Udine, Polytechnic Department of Engineering and Architecture (DPIA), Via del Cotonificio 108, 33100 Udine, Italy
(E-mail: *moretti.alessandro@spes.uniud.it; matia.mainardis@uniud.it)*
*** Acque Bresciane S.r.L., Via Cefalonia 70, 25124 Brescia, Italy
(E-mail: *luigi.rizzo@acquebresciane.it; sonia.bozza@acquebresciane.it; mauro.olivieri@acquebresciane.it)*

Abstract
The growing interest towards wastewater (WW) reuse as alternative irrigation source is raised by the worldwide concern on water shortages and enhanced by the new European Directive on water reuse minimum requirements. In this perspective, water utilities and decision makers would benefit from a methodology to evaluate and encourage safe and efficient agricultural WW reuse practices. In this work, we propose a novel approach to identify criteria for assessing and prioritizing WW treatment plants (WWTPs) suitability for WW reuse practices implementation. The developed methodology, coupling WWTPs' characteristics (i.e., flowrate and effluent quality) and features of the local territory (i.e., cultivated crops and climate), is able to quantify the economic savings, in terms of water and nutrients, and avoided environmental impacts, that could be fulfilled from WW reuse, and which WWTPs and territories to prioritize in its implementation.

Keywords (maximum 6 in alphabetical order)
Economic savings; Fertigation; Greenhouse Gas emission; Holistic framework; Nutrients; Sustainability; Wastewater reuse.

INTRODUCTION

The scarcity of fresh water is one of the major challenges faced by humankind today. In this context, agriculture is the sector with the major water demand, accounting for about 70% of global freshwater withdrawals. Water for crops irrigation is typically extracted from natural sources, reducing the freshwater availability and exposing the agricultural sector to a great impact from water shortages (López-Serrano et al., 2020). On the other hand, the reuse of reclaimed municipal wastewater (WW) provides a reliable water source, with continuous and stable production throughout the year. In addition, it is a source of water and nutrients, as nitrogen (N) and phosphorus (P), also contributing to the reduction of green-house gases (GHGs) emissions compared to traditional management approaches, avoiding WW overtreatment and mineral fertilisers addition.

More stringent regulations are continuously proposed on WW quality aimed at direct reuse for irrigation in agriculture, as for the European Union, where the new Directive establishes limits and minimum requirements for reclaimed WW reuse in agriculture (EU Commission, 2020). In this perspective, water utilities, often managing hundreds of wastewater treatment plants (WWTPs) of extremely different sizes and characteristics, would benefit from a prioritization methodology, currently missing, that might help them in selecting the most appropriate WWTPs for reuse implementation. This approach should couple both WWTP (i.e., flowrate and effluent quality) and territory (i.e., crops and climate) characteristics. Mainardis et al. (2022) proposed a methodological approach to preliminarily assess the techno-economic sustainability and feasibility of WW reuse that was applied to a single case-study.

In this work, the model proposed by Mainardis et al. (2022) was upgraded in an holistic framework, including water and nutrients mass balance, economic and environmental impacts assessment. This framework was applied to several Italian WWTPs to: (i) quantify the amount of water and nutrients needed by the crops that could be fulfilled by WW; (ii) evaluate fertigation sustainability over traditional practices; (iii) rank WWTPs and local territory characteristics improving WW reuse feasibility; (iv) determine prioritization criteria for WW reuse practices implementation.

MATERIALS AND METHODS

Irrigation water volumes to be delivered to satisfy crops requirements were estimated based on monthly water balances during the irrigation season (May to September). In the adopted approach, specific crops' evapotranspiration (ET, L s^{-1} ha^{-1}) was considered equal to their water requirement (Mainardis et al., 2022). Thus, the net irrigation requirement (I, L s^{-1} ha^{-1}), which is the necessary fertigation water volume to be provided to the crops, was obtained as reported in Eq. (1):

$$I = \frac{ET - R}{E} \tag{1}$$

where R (L s^{-1} ha^{-1}) is the effective rainfall, determined from metereological data through Turc's equation, while E is the overall irrigation efficiency, calculated multiplying (i) irrigation system efficiency, (ii) water distribution efficiency from source to fields, and (iii) application efficiency.

Regarding nutrients, N and P were considered being the ones reported by current reuse regulations. Mass balances were drawn comparing monthly crop nutrient requirements (kg $month^{-1}$ ha^{-1}) and nutrients concentrations of the applied WW volumes, accounting for fertilizer use efficiency. When fertigation-supplied nutrients do not meet crop requirements, mineral fertilizers should be added; in the opposite case, fertigation limitation occurs, resulting in a reduction in the water applied, which should be supplemented with other sources.

Once the amounts of water and nutrients deliverable from the WWTP were calculated, two different outputs were obtained. Firstly, an economic evaluation was performed to quantify water and mineral fertilisers savings. Agricultural water supply cost was considered for water saving estimation. The cost of mineral fertilizers (ammonium nitrate for N, triple super phosphate for P), with their use efficiency were considered. Secondly, the GHGs emission savings due to the reduction of applied mineral fertilisers has been estimated by applying a GHG conversion factor (5.79 kg_{CO2EQ} kg_N^{-1} for N and 0.63 kg_{CO2EQ} kg_P^{-1} for P) (Jiménez-Benítez et al., 2020).

The developed model was applied to 95 municipal WWTPs in two major areas in northern Italy, with a served population equivalent (PE) higher than 2,000 inhab for each WWTP, and close to suitable crop fields. These WWTPs were grouped in different clusters with similar characteristics based on three clusterization parameters: (i) WWTPs size, divided into small (S, PE=2,000-10,000 inhab), medium (M, PE=10,000-70,000 inhab) and large (L, PE>70,000 inhab) WWTPs, (ii) WWTPs nutrient removal, divided into absence of nutrients removal (NO), only N removal (N) and combined N and P removal (NP), and (iii) main crops cultivated nearby the WWTP, divided into seed crops (SEED, maize or soybean) and fruits and vegetables crops (F/V, carrot or vines). The latter parameter was considered due to the significant difference in terms of water required from these two types of crops. One or more representative WWTPs were selected for each cluster, based on the availability and reliability of effluent quality data. For the selected WWTPs, data about median monthly flowrate and N and P concentrations in the effluent, together with the monthly cumulated rainfall and the type of crops nearby the WWTP, were collected.

RESULTS AND DISCUSSION

Ten clusters were determined based on the adopted clusterization parameters, from which the cluster's ID code was derived. Table 1 reports the clusters' characteristics.

For S-WWTPs and M-WWTPs, the evaluation of a single WWTP was sufficient to give a realistic representation of the whole cluster, since the collected data did not show significant differences. Instead, for L-WWTPs' clusters, more than one WWTPs were considered for model application, given the significant variability of the treatment trains; thus, 14 WWTPs were considered in total in the following analysis.

Table 1. Summary of clusters' characteristics: number of available and selected WWTPs, WWTPs flowrate, N and P concentrations, indicated as average and range in brackets.

Cluster ID	#available WWTPs	#considered WWTPs	Flowrate (m^3 day^{-1})	N concentration (mg L^{-1})	P concentration (mg L^{-1})
S-NO-SEED	5	1	1,454 (652 – 9,005)	18.24 (6.8 – 29.2)	1.49 (0.4 – 3.1)
S-NO-F/V	2	1	243 (212 – 249)	11.25 (3.3 – 22.6)	1.57 (0.4 – 2.5)
S-N-SEED	39	1	2,098 (1,337 – 4,144)	9.29 (4.9 – 23.2)	0.68 (0.3 – 1.7)
S-N-F/V	24	1	675 (249 – 1,663)	12.47 (6.1 – 26.2)	2.70 (0.7 – 4.3)
S-NP-SEED	4	1	397 (344 – 442)	6.67 (2.0 – 13.6)	1.19 (0.2 – 2.4)
S-NP-F/V	5	1	323 (137 – 342)	5.97 (1.5 – 17.8)	1.33 (0.1 – 2.7)
M-NP-SEED	6	1	4,176 (1,800 – 11,026)	4.51 (0.3 – 12.9)	0.31 (0.1 – 1.3)
M-NP-F/V	4	1	7,352 (3,647 – 14,465)	9.44 (2.4 – 20.0)	0.68 (0.3 – 2.7)
L-NP-SEED	4	4	19,519 (8,097 – 38,439)	7.40 (1.5 – 16.1)	0.62 (0.1 – 3.3)
L-NP-F/V	2	2	102,229 (7,879 – 176,662)	6.71 (3.4 – 11.0)	0.70 (0.3 – 1.6)

Based on the developed methodology, three outputs were estimated to assess the suitability of the implementation of WW reuse practices: total (i) water and (ii) fertiliser cost savings, and (iii) avoided GHGs emission on the considered period (April to September). For every WWTP, the model was run twice for both types of crops: in SEED for maize and soybean, in F/V for carrots and vines, since they are both present in the WWTPs proximity. As for water, fertilisers and GHG emission savings as a function of different clusters' characteristics (Figure 1), it is evident that different categories of the clusterization parameters affect the distribution of the single clusters' output.

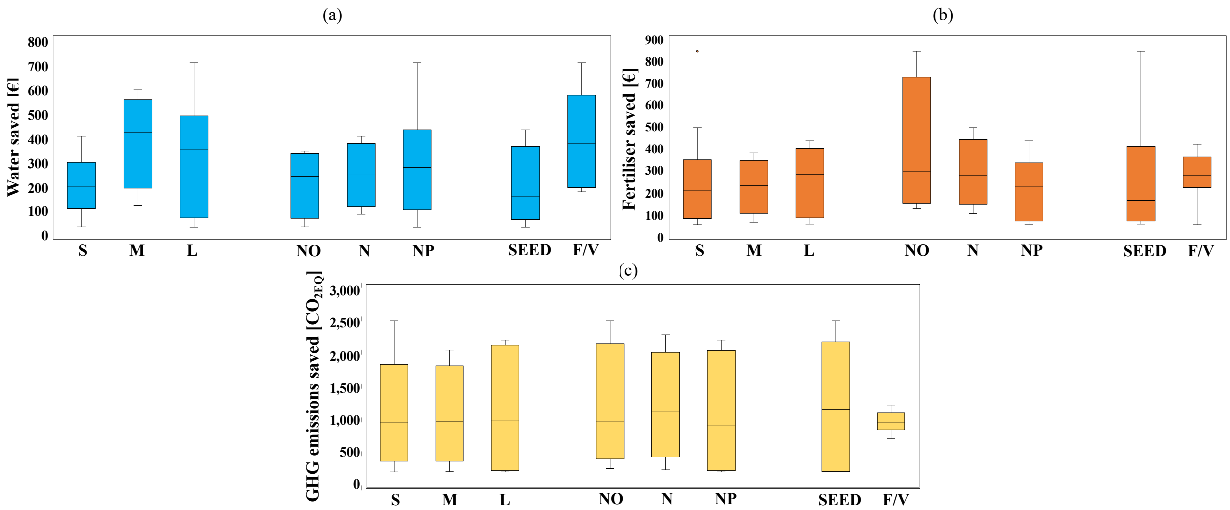

Figure 1. Estimated savings of (a) water, (b) fertilisers and (c) GHG emission differentiated per clusterization parameters.

Regarding the WWTP size, being the size directly proportional to the quantity of treated flowrate (and, thus, of the WW available for reuse), the most affected output is the water cost saving, being on average half for S-WWTPs compared to M- and L-WWTPs. However, conversely to what was expected, L-WWTPs and M-WWTPs water cost savings are not significantly different, due to the limitation in crops nutrients' requirement, which caps the amount of WW deliverable to the crops. For the WWTP's nutrient removal treatment, passing from NO-WWTPs to NP-WWTPs, a slight reduction of the median fertiliser cost savings is observed, and only NO-WWTPs show fertilizers saving over 500 €. This confirms that a lower extent of nutrient removal implies a lower supply of mineral fertilisers to the crops and, thus, a higher saving in fertilisers' cost. Finally, for all the considered outputs, the crop type emerged as the most relevant clusterization parameter. In fact, for each output, the results' distributions vary significantly between SEED-WWTPs and F/V-WWTPs, both in terms of median values and variabilities, meaning that the crops surrounding the WWTP are a fundamental characteristic to consider when a WW reuse practice is evaluated.

The economic savings (given by both water and fertilizers savings) and avoided GHG emissions were plotted in a Pareto chart in Figure 2, for all case studies (14 WWTPs for 2 types of crops), differentiated by cluster. Three distinct groups of WWTPs are evident for GHGs emission savings, which are located on three different horizontal levels. These groups vary only for the specific type of crops, in particular, within SEED-WWTPs, maize-based crops give the best emission savings (mean value of 2,200 kg_{CO2EQ}), but, on the other side, soybean-based crops give the worst ones (mean value of 230 kg_{CO2EQ}). This confirmed the high variability associated with SEED-WWTPs' boxplots in Figure 1b,c. Instead, for F/V-WWTPs, both carrot- and vines-based crops lay on the same horizontal line (mean value of 1,000 kg_{CO2EQ}). Once again, it is confirmed the oustanding relevance of the specific type of crop that is present close to the WWTP in determining WW reuse sustainability. On the other hand, the influence of WWTPs characteristic on economic savings depends on the crop type.

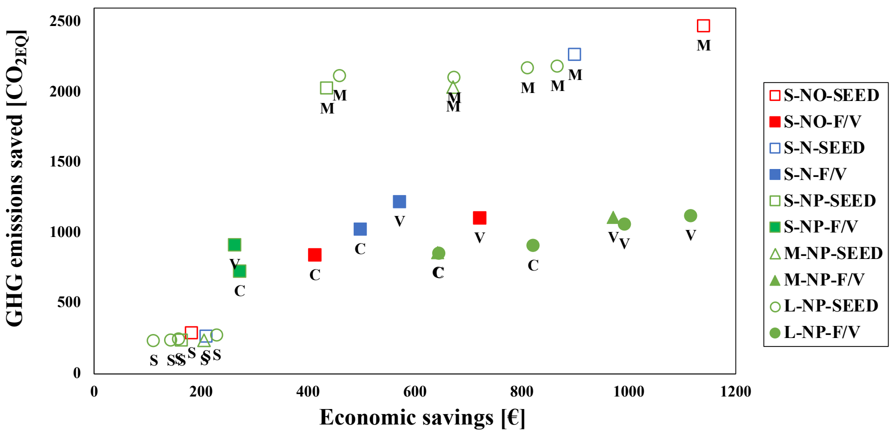

Figure 2. Pareto diagram of all the estimated outputs. The letters refer to the specific crop analysed: M=maize, S=soybean, C=carrots and V=vines.

To conclude, this work highlighted the potential of the developed methodology to rank the characteristics of WWTPs' and their nearby territory for determining useful criteria for the prioritization of WW reuse practices implementation. Further research is needed to validate these results considering other WWTPs, in order to obtain an adaptive methodology that might be applied to a few WWTPs aiming at extending the results to a broader sample of WWTPs.

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