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Agro-industrial Treated Wastewater Reuse for Crop Irrigation: Implication in Soil Fertility

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At the same time with population In many arid and semi-arid countries water is becoming an increasingly scarce resource and so it is fundamental to consider any sources of water including treated agro-industrial wastewater which might be used economically and effectively to promote further development. This study was carried out at Fiordelisi company (Stornarella; 41° 15'N, 15° 44'E; altitude, 154 m a.s.l.), which produces processing vegetables (i.e., tomato, broccoli, eggplant, zucchini, pepper) and is equipped with a wastewater treatment plant based on the following steps: screening, oil removal, equalization, activated sludge process (anoxic plus aerobic phases), chemically assisted sedimentation, sand filtration (preceded by chlorination), membrane ultrafiltration (Kristal 600ER -Hyflux - nominal pore size of 0.05 μm), UV disinfection (6 mercury-vapor lamps, 300W each). During the study three types of water (groundwater - GW -; secondary treated agro-industrial wastewater -SW - and tertiary treated agro-industrial wastewater -TW -) were used for irrigation of processing tomato and broccoli crops, to evaluate the main effects on plant nutrient contents of the soil. The experimental trials were carried out in open field over three growing seasons of the considered crops, from April 2012 to February 2015. Compared to GW, SW and TW were characterized by higher contents of plant nutrient, such as NH_4-N,NO_2-N, PO_4^{2-}, K^+, Ca^{2+}, Mg^{2+}, TSS and organic matter. On the contrary, GW showed higher NO_3-N content. However, considering the seasonal irrigation volumes applied to tomato and broccoli crops, a significantly nutrients load in the soil was observed only for K^+ and NO_3-N.
Keywords: agro-industrial wastewater; irrigation; soil fertility.

1. Introduction

In recent years, the continuous growth of world population along, the intensification of industrial and agricultural activities for increasing food supply and the more and more prolonged droughts, have caused the consumption of existing water resources until reaching their maximum amount in arid and semi-arid regions. Therefore, any sources of water which might be used economically and effectively should be considered to promote further development. In regions with limited natural water sources, treated wastewater including agro-industrial one must be taken into account for agricultural and industrial use.

Apulia region (Southern Italy) as a semi-arid area, suffers from shortages of water supply for domestic, industrial and agricultural purposes. On the other hand, the production system of Apulia Region is characterized by numerous agro-food industries, whose activity produces large quantities of wastewater usually discharged into torrents or rivers. In this contest, a careful management of agro-industrial wastewater for agricultural and industrial use, after a indispensable tertiary treatment, represents a useful alternative to conventional water resources. Indeed, to eliminate or at least reduce the chemical and microbiological wastewater contaminant (partly coming from toilets) and then minimize the risk of crop contamination, high-technology tertiary treatments and disinfection systems, such as activated carbon, reverse osmosis, membrane filtration, chlorination, ozonation, UV irradiation are essential (Asano and Levine, 1998).

The effects of chemical and microbiological characteristics of the treated wastewaters used in this experimental trial has already been discusses in previous studies (Gatta et al., 2015(a) and (b); Tarantino et al., 2015) that investigated the quantitative, qualitative and microbiological traits of the tomato and broccoli yields, These studies reported that soils and plants irrigated with treated agro-industrial wastewater were not

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contaminated with fecal indicators generally associated with human health risks, In addition, the main results of previous studies showed that irrigation of tomato and broccoli plants with agro-industrial wastewater did not negatively affect main qualitative parameters. Therefore, such treated agro-industrial wastewater application appears to constitute a valid alternative for irrigation of tomato and broccoli.
Treated agro-industrial wastewater offers not only an alternative to conventional water irrigation sources, but might also provide the opportune to recycle plant nutrient. Indeed, treated wastewater can contain useful easily biodegradable organic matter and readily absorbable plant nutrients, such as nitrogen (N), phosphorous (P), potassium (K) and magnesium (Mg).
Application of wastewater to cropland is an attractive option for disposal because not only provides water but it can also improve physical properties and nutrient contents of the soils (Pomares et al., 2004).
The main objective of the present study was to verify the possibility of a long-term re-use of agro-industrial wastewater originated from a processing vegetable company for crop irrigation and the effects that this might have on the plant nutrient supply. Three water sources were used: groundwater (GW), secondary treated wastewater (SW) and tertiary treated wastewater (TW). These provided the irrigation source of a test filed where tomato and broccoli crops were cultivated in close succession over 3 years.

2. Materials and Methods

2.1 Wastewater treatment plant

The "Fiordelisi" company produces on average about 46,500 m^3y^{-1} of wastewater, which is mainly composed of process water (vegetables processing and cleaning),water from the bottles washing line and water from the toilets (5 to10% of the total). The operation of wastewater treatment plant, schematized in Figure 1, is based on the following steps: primary treatment (screening, oil removal, equalization and pH adjustment); secondary treatment - SW - (activated sludge process - anoxic plus aerobic phases - and chemically assisted secondary sedimentation); tertiary treatment - TW (preceded by chlorination), (sand filtration, membrane ultrafiltration (nominal pore size of 0.05 μm; Kristal 600ER -Hyflux) and UV radiation (six mercury-vapor lamps, 300W each).

2.2 Field experiments layout

The experimental trials were carried out in open field near to "Fiordelisi" wastewater treatment plant, over a close succession of three tomato and broccoli crop cycles, from April 2012 to March 2014, at Stornarella (41° 15'N, 15° 44'E; altitude, 154 m a.s.l.), Apulian Region, South-Italy During the study, the three types of water were used for crop irrigation: GW (control), SW and TW. GW was pumped from a phreatic well located near the experimental field. This represents the irrigation source normally used by the local farmers for crop irrigation.The trial was carried out on a clay-loam soil (USDA classification), characterized by as and content of 39.8%; loam content of 33,1% and clay content of 328.0%. The soil showed a field capacity (-0.03 MPa) of 30.5% on dry weight (dw), a wilting point (-1.5 MPa) of 15.9% dw and a bulk density of 1.41±0.03 Mg m^{-3}.
The study was carried out according to a complete randomized block design with each of the three irrigation treatments (i.e. GW, SW and TW) replicated three times. The crops were grown in four identical plots of 450 m^2 (15 m wide x 30 m long) with a sampling area of 20 m^2 (2.5 m wide x 8.0 m long).

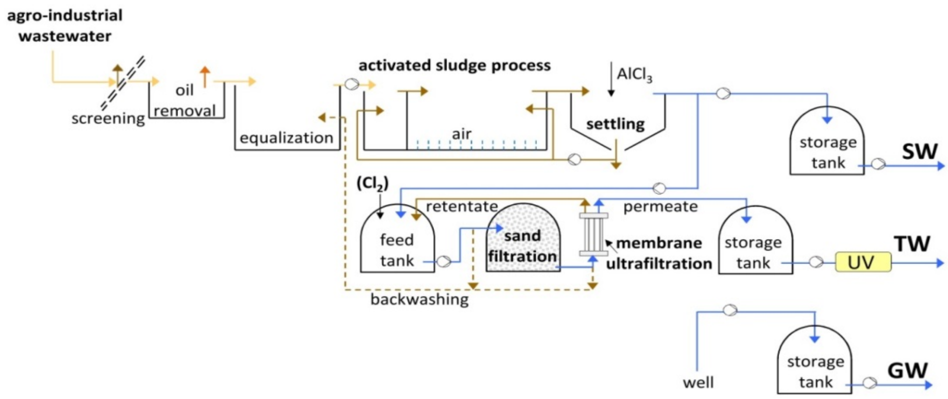

Figure 1: Configuration of the wastewater treatment plant operated at "Fiordelisi" company. The scheme shows the treatment processes that each type of irrigation water (SW, TW, and GW) underwent before being used in the field experiments.

The seedlings of processing tomato (*Lycopersicon esculentum* Mill., cultivar "Manyla") were transplanted within the first 10 days of April 2012, 2013 and 2014, in double rows (40 cm apart) spaced at 250 cm, at the distance of 30 cm along each single row. The final plant density was equal to 2.7 plants m^{-2}. A drip irrigation method was used, with the drip lines placed between each couple of plant rows, under a black plastic mulching film. The tomato plants were grown vertically, under a net house structure, which was covered with an anti-hail net using nylon threads positioned between the plant collar and iron wires, arranged longitudinally in the direction of the plant rows and fixed to the upper part of the net house, at 2.5 m from the ground. Tomato fruits were hand harvested at full red maturity stage several times from July to September 2013, 2014 and 2015, at approximately two-week intervals.

The seedlings of broccoli (*Brassica oleracea* L. var. *italica*, ibrid "Partenon" F_1) were transplanted in close succession to the tomato crops within the first 10 days of October 2012, 2013 and 2014, in in double rows (40 cm apart) spaced at 250 cm, at the distance of 30 cm along each single row. The final plant density was equal to 2.7 plants m^{-2}. Also for broccoli crop drip irrigation method was adopted, with the drip lines placed along the plant rows. The broccoli heads with 15 cm of stem and without leaves were harvested on February 2013, 2014 and 2015 .During each crop cycle, the plants were irrigated whenever the soil water deficit in the effective root zone (0-50 cm in depth) was 40% of the total available soil water (Allen *et al*., 1998). This irrigation threshold was assessed thanks to a continuous monitoring of the volumetric soil water content using probes operating in the frequency domain reflectometry and installed in each plot prior to crops transplanting at 15, 25, 35 and 45 cm soil. At each irrigation, the soil water content of each plot was increased to field capacity with a water volume varying from 100 to 300 m^3 ha^{-1}, depending on the crop growth stage.

The seasonal irrigation volumes applied during the tomato crop cycles were 4957; 3817 and 3718 m^3 ha^{-1} in 2012, 2013 and 2014, respectively. During the broccoli crop cycles seasonal water volumes were 920, 874 and 892 m^3 ha^{-1} in 2013, 2014 and 2015, respectively.

All the agricultural management practices, such as fertilization, weed and pest control, applied to the crops during the experimental trial, were those commonly adopted by local farmers.

2.3 Climate conditions of the experimental site

The mean monthly values of the main climate parameters recorded in the course of each growing cycle of tomato (from April to August 2012, 2013 and 2014) and broccoli (from October 2012, 2013 and 2014 to February 2013, 2014 and 2015), are reported in Table 1.

These were measured by a weather station and store by a data-logger (Campbell Scientific, USA) both located near the experimental site.

Table 1: Mean monthly maximum and minimum air temperatures, total rainfall and total "Class A" pan evaporation during the processing tomato and broccoli crop cycles.

Climatic parameters	Tomato 2012-2013-2014						Broccoli 2012-2013 2013-2014 2014-2015					
	Apr	May	Jun	Jul	Aug	Total growing season	Oct	Nov	Dic	Jan	Feb	Total growing season
T_{MAX} (°C)	19.9	23.7	29.9	31.9	10.9	27.6	22.7	17.8	13.0	12.4	12.8	15.7
T_{MIN} (°C)	8.7	9.5	19.0	19.7	19.4	13.6	12.4	11.0	5.7	4.5	4.3	7.0
Rainfall (mm)	78.4	45.8	43.2	24.7	50.3	242.6	62.6	113.9	88.0	97.5	74.9	414.8
E (mm)	79.9	118.5	150.4	166.5	155.8	670.8	50.2	26.8	15.6	19.1	27.9	139.7

2.4 Water and soil sampling

Triplicate samples of GW, SW and TW were collected from under the drippers, at monthly intervals, during the tomato and broccoli growing cycles. Water samples were kept in a refrigerator at +4 °C and examined within 24 h of their collection, according to Standard Methods (APHA-AWWA-WEF, 1998).

2.5 Statistical Analysis

The data concerning the qualitative parameters of irrigation water applied during the tomato and broccoli cycles were processed statistically through analysis of variance (ANOVA), and when significant effects were detected ($P \leq 0.05$), mean multiple comparisons were performed according to Tukey's tests. All of the analyses were performed using the JMP software (JMP, 2008).

3 Results and Discussion

3.1 Irrigation water properties

Table 2 shows the average values of the main physico-chemical characteristics of GW, SW and TW measured over the three tomato and broccoli crops respectively. The Italian standards for wastewater re-use in irrigation (Decree No. 185, 2003, Ministry for Environment) are also reported.

3.2 Physicochemical Characteristics of the Irrigation Waters

The irrigation water properties varied considerably among the GW, SW and TW, with little difference among the crop cycles. Overall, the main physico-chemical properties of the three types of water sources met the Italian standards for wastewater re-use for irrigation, except for the TSS and BOD_5 both in SW and TW, that exceeded the legal threshold values set by the above mentioned legislation. More specifically. the TSS in SW and TW during the tomato crop cycles were on average equal to 45.74 mg l^{-1} and 46.44 mg l^{-1}, respectively, and for the broccoli crop cycles 60.93 mg l^{-1} and 55.31 mg $l^{-1,}$ respectively (Table 2). Moreover, the BOD5 values in SW and TW observed during the tomato cycles were 23.00 mg l^{-1} and 35.43 mg l^{-1}, respectively, and for broccoli 30.55 mg l^{-1} and 28.4 mg $l^{-1,}$ respectively.

As to average values of the tomato and broccoli growing seasons, the three types of water were always alkaline, with pHs ranging from 7.33 to 7.87 (Table 2). These values were not significantly different among them. If compared with GW, SW and TW were always characterizsed by higher amounts of N (as NH_4-N and NO_2-N), PO_4-P, K^{2+},Ca^{2+}, Mg^{2+}, TSS and OM (as indicated by the TSS, BOD_5 and COD values).

The higher levels of these chemical parameters in the two treated agro-industrial wastewaters indicate that SW and TW are of particularly important from an agronomic point of view, since they act as a sources of plant nutrients, thus contributing to soil fertility and crop yield increases. So they need to be taken into account in crop fertilization practices (Vergine et. al., 2016).

This aspect has also been highlighted in another study related to the re-use for crop irrigation of reclaimed wastewaters derived from simplified tertiary treatments that did not include the biological processes, in order to preserve the agronomic potential of the OM and nutrients contained in wastewaters (Lopez et al., 2006;). In addition, SW and TW were characterizsed by significantly higher EC, Na^+, and SAR, if compared to GW. Nevertheless if the SAR of SW and TW are related to the EC, it appears that there is no limit to the agricultural application of both this type of agro-industrial wastewaters, and there would be no reduction in its rate of infiltration into the soil (Ayers and Westcot, 1985).

Over the whole experimental period, GW showed significantly higher average values of NO_3-N (26 and 20,41 mg l^{-1}, for tomato and broccoli crop cycles respectively than SW (0.68 and 0.59 mg l^{-1}, for tomato and broccoli crop cycles respectively) and TW (1.13 and 1.01 mg l^{-1}, for tomato and broccoli crop cycles respectively). This elevated NO_3-N content in GW is due to nitrate contamination of the aquifer in the study area, where the intensive agricultural activity has led to an extensive application of nitrogen fertilizer to the crops. The resulting nitrogen surplus in the soil is then particularly exposed to the risk of leaching, thus increasing the environmental problem of nitrate pollution. Moreover, this high NO_3-N content in GW represents an important nutrient source for the crops, but unfortunately it is not taken into account by farmers in their crop fertilization plans. The carbonate, bicarbonate and SO_4− contents showed similar levels in all the three types of the irrigation waters.

3.3 Nutrients source for the crops

As previously reported, the NO_3-N content of GW was significantly higher than SW and TW. On the contrary, in the two types of treated agro-industrial wastewater, the content of plants nutrients, such as N (as NH_4-N and NO_2-N), PO_4^{2-}, K^+, Ca^{2+}, Mg^{2+} and organic matter (OM) were significantly higher than those measured in GW. Considering the seasonal irrigation volumes of GW, SW and TW applied to the crops during the trial, which as average value of the three tomato and the three broccoli growing seasons resulted equal to 4130 m^3 ha^{-1} and 895 m^3 ha^{-1} respectively, and the corresponding concentrations of the above mentioned nutrients, the crops received higher levels of NO_3 with GW than with SW and TW, and higher levels of K with SW and TW than GW (Table 3).

More specifically, irrigation with GW accounted, on average, for a further 116.4 NO_3-N kg ha^{-1} in tomato and 18.3 NO_3-N kg ha^{-1} in broccoli. This additional nitrogen amount provided by GW represents approximately 60% of nitrogen requirement of tomato crops and 15% of nitrogen requirement of broccoli crops. Similarly, as to the growing cycles of tomato crop, irrigation water accounted for a further average K^+ amount equal to 262.43 K kg ha^{-1} and 239.41 K kg ha^{-1} with TW treatment. As to broccoli crop cycles, a further average K^+ levels of 49.9 K kg ha^{-1} with SW and 47.5 K kg ha^{-1} with TW was observed.

The additional K^+ amounts provided by irrigation with both SW and TW, if compared with crops requirement, represents approximately 60%, for tomato and approximately 30% for broccoli.

Table 2: Means of the main-physico-chemical parameters measured in groundwater (GW), secondary agro-industrial treated wastewater (SW) and tertiary treated agro-industrial wastewater (TW), during the irrigation periods of tomato and broccoli crops, grown in close succession over three years.

Parameter	Italian Limit for irrigation reuse (M. D.185/2003; R.R. 8, 2012)	TOMATO				BROCCOLI			
		GW	SW	TW	Sign	GW	SW	TW	Sign
pH	6.0 -9.5	7.69 ± 0.07	7.56 ± 0.07	7.59 ± 0.07	ns	7.87 ± 0.20	7.33 ± 0.108	7.53 ± 0.09	ns
EC (dS m^{-1})	3.00	0.51 ± 0.11	2.44 ± 0.28	2.89 ± 0.26	*	2.33 ± 0.20	2.72 ± 0.24	2.61 ± 0.35	*
TSS (mg l^{-1})	10	3.0.5 ± 0.99	45.05 ± 2.40	46.44 ± 1.95	*	4.55 ± 1.12	66.55 ± 19.23	55.31 ± 16.66	*
NH_4-N (mg l^{-1})	2 (15)[a]	0.05 ±0.00	2.15 ±0.61	2.75 ±0.78	*	0.04 ±0.01	0.13 ± 0.03	0.09 ±0.11	*
NO_3-N (mg l^{-1})	35 (15)[b]	26.00 ± 1.37	0.68 ±0.13	1.13 ±0.77	*	20.41 ± 1.08	0.59±0.18	1.01 ± 0.43	*
NO_2-N (mg l^{-1})	-	0.07 ± 0.04	0.09 ± 0.03	0.14 ± 0.05	*	0.01 ± 0.00	0.02± 0.01	0.04 ± 0.00	*
PO_4-P (mg l^{-1})	10 (2)[b]	0.11±0.01	0.45 ±0.06	0.28 ±0.06	*	0.10±0.01	0.55 ±0.13	0.47 ±0.07	*
BOD_5 (mg l^{-1})	20	10.50 ± 0.78	23.00 ± 1.20	35.43 ± 7.70	*	4.32 ± 0.48	30.55 ± 4.77	28.11 ± 5.11	*
COD (mg l^{-1})	100	17.64 ± 1.65	59.64 ± 10.98	71.65 ± 18.60	*	6.42 ± 2.23	54.32 ± 9.87	49.27 ± 10.09	*
Na^+ (mg l^{-1})	-	33.73 ± 1.27	267.09 ± 13.62	305.50 ± 16.01	*	39.51 ± 1.56	268.74 ± 6.76	272.12 ± 12.01	*
Ca^{2+} (mg l^{-1})	-	77.12 ± 4.42	84.09 ±4.56	82.70 ± 5.44	ns	87.54 ± 4.51	84.45 ± 2.39	84.31 ± 0.51	ns
Mg^{2+} (mg l^{-1})	-	10.24 ± 0.63	10.45 ± 0.48	10.48 ± 0.71	ns	11.68 ± 0.07	10.76 ± 0.16	10.84 ± 1.76	ns
K^+ (mg l^{-1})	-	13.33 ± 2.94	55.02 ± 4.46	63.68 ± 5.73	*	10.60 ±0.35	55.80 ± 3.50	53.07 ± 2.35	*
CO_3^{2-} (mg l^{-1})	-	164.27 ± 3.62	159.02 ± 7.38	144.64 ± 8.58	ns	159.88 ± 2.78	140.91 ± 10.93	151.30 ± 12.76	ns
HCO_3^- (mg l^{-1})	-	256.12 ± 6.19	236.69 ± 18.74	254.64 ± 22.68	ns	235.09 ± 5.79	232.03 ± 11.04	222.05 ± 16.90	ns
SO_4^- (mg l^{-1})	500	32.36 ± 2.0.6	27.34 ± 1.83	25.15 ± 2.91	ns	28.94 ± 1.81	29.99 ± 3.32	30.54 ± 2.26	ns
SAR	10	1.07 ± 0.02	7.01 ± 0.19	7.62 ± 0.20	*	1.01 ± 0.02	7.16 ± 0.08	7.04 ± 0.18	*

Each data is mean±standard error, determined on 15 samples. [a] Limit concentration for ammonium can be raised to the value in brackets (R.R. 8, 2012). [b] Limit concentration for total nitrogen and total phosphorus (in brackets the limit concentration for vulnerable areas to nitrate and phosphate). * Statistically significant at P≤ 0.05; ns, not significant.

Table 3: Supply of mineral nutrients to the soil by the three irrigation water types (GW, Groundwater; SW; Secondary agro-industrial wastewater; TW, tertiary agro-industrial wastewater), according to the average values of three growing cycles of tomato and broccoli crops, respectively

Irrigation treatment	Seasonal irrigation volume ($m^3 ha^{-1}$)	Nutrient supply by irrigation water (kg ha^{-1})			
		NH_4-N	NO_3-N	PO_4-P	K
	Tomato 2012 2013 2014				
GW	4130	0.21	116.4	0.48	53.56
SW	4130	8.22	3.03	1.82	262.43
TW	4130	4.83	4.32	1.07	239.41
	Broccoli 2013-2013 2013-2014 2014-2015				
GW	895	0.039	18.30	0.09	9.48
SW	895	0.12	0.53	0.49	49.86
TW	895	0.30	0.92	0.41	47.35

4. Conclusions

In the present study, the long-term re-use of SW and TW for irrigation of tomato and broccoli crops cultivated in close succession over a period of three years was compared with conventional GW.
SW and TW, deriving from a reclamation process of wastewater produced by an agri-food company which cultivates and processes vegetables, were characterizsed by higher levels of several chemical parameters than GW. The two treated agro-industrial wastewaters showed higher content of plant nutrients, such as NH_4-N, NO_2-N, PO_4-P, K^+, Ca^{2+}, Mg^{2+}, BOD_5, COD and TSS; on the contrary GW showed higher concentration of NO_3-N. Considering the seasonal irrigation volumes applied to tomato and broccoli crops during the experimental trial, a significant contributions of nutrients from the treated agro-industrial wastewaters have been observed. Particularly high resulted the potassium supply. For GW a high NO_3-N contribution was detected. Under the conditions of this study, the findings of the experimental activity indicate that treated agro-industrial effluents have the potential to provide good amounts of nutrients which would be taken into account by farmers in the crop in the fertilization plans.

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