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Ambiance rose production and nutrient supply in soil irrigated with treated sewage

Giuliano Gabrielli[1], Jorge L. da Paixão Filho[1], Bruno Coraucci Filho[1] & Adriano L. Tonetti[1]

[1] Faculdade de Engenharia Civil Arquitetura e Urbanismo/Universidade Estadual de Campinas. Campinas, SP. E-mail: gironozoo@gmail.com (Autor correspondente); jorgepaixao@gmail.com; bruno@fec.unicamp.br; adriano@fec.unicamp.br

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A B S T R A C T

Effluents from secondary sewage treatment plants may contain amount of nutrients with the potential to cause eutrophication of water bodies. One of the ways to decrease this influx of nutrients would be the agricultural reuse. Therefore, the objective of this study was to evaluate the irrigation of roses of the Ambiance variety with the effluent from an anaerobic reactor and an intermittent sand filter (nitrified effluent). The trial lasted for 152 days. The dose of nitrogen applied via effluent was 91% of the crop requirement; of phosphorus, 3.5% (very low); and of potassium, 23%. There was no difference among treatments for the evaluated variables: diameter and length of stem, diameter and length of bud, and fresh weight of flower buds. The production of floral stems was higher in treatments with effluents without conventional fertilization. It is concluded that the irrigation with a treated effluent is an alternative for the fertilization of ambiance roses.

Palavras-chave:
reúso de esgoto
pós-tratamento
eutrofização

Produção de rosas Ambiance e aporte de nutrientes em solo irrigado com esgoto tratado

R E S U M O

Efluentes de estações de tratamento secundário de esgoto podem conter quantidades de nutrientes com potencial para causar a eutrofização de corpos d`água. Uma das maneiras de diminuir esse afluxo de nutrientes seria pelo reúso agrícola. Portanto, o objetivo deste trabalho foi avaliar a irrigação de roseiras da variedade Ambiance com efluente de reator anaeróbio e de filtro de areia intermitente (efluente nitrificado). O experimento durou 152 dias. A dose de nitrogênio aplicada via efluente foi de 91% da necessidade da cultura; a de fósforo 3,5% (muito baixa) e a de potássio 23%. Não houve diferença entre os tratamentos para as variáveis avaliadas: diâmetro e comprimento da haste, diâmetro e comprimento do botão e peso fresco do botão floral. A produção de hastes florais foi maior nos tratamentos com efluentes sem adubação convencional. Concluiu-se que a irrigação com efluente tratado é uma alternativa para a fertilização de roseiras ambiance.

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Introduction

Effluents from sewage treatment plants with a secondary treatment level may still contain a harmful amount of nutrients for the environment. The launch of these effluents in water bodies can lead to eutrophication, thus decreasing the quality of surface waters. In addition, they could harm the aquatic life and the use of water by the population (Carey & Migliaccio, 2009).

The use of this type of wastewater can be a way to reduce or even eliminate the discharge of nutrients in receiving bodies. In this case, there would be the use of nutrients for agricultural production, which would reduce the costs with the use of mineral fertilizers (Carey & Migliaccio, 2009; Qadir et al., 2010).

Some studies bring estimates of the amount of nutrients that the agricultural reuse of treated sewage offers. According to Gomes et al. (2009), when working on the irrigation of sugarcane for nine months with stabilization pond effluent, there was a nitrogen supply of 149 kg ha^{-1} and a phosphorus supply of 14 kg ha^{-1}. That would amount to 199 kg ha^{-1} $year^{-1}$ of nitrogen and 18.67 kg ha^{-1} $year^{-1}$ of phosphorus. According to the author, the nitrogen supply satisfies the crop fertilization requirements regarding this nutrient. Segal et al. (2011) watered olive trees with secondary sewage effluent and achieved productivity and quality equivalent to the conventional cultivation method.

In Tula Valley (Mexico), irrigation with effluent offers 195 kg ha^{-1} $year^{-1}$ of nitrogen and 81 kg ha^{-1} $year^{-1}$ of phosphorus (Jimenez, 2005). This amount of nutrients added to the soil by effluents provides a productivity equivalent to or higher than the one obtained with traditional cultivation (mineral fertilizer and clean water).

In Brazil, it would be possible to adopt this practice in the irrigation of flower crops, which require high levels of water and nutrients (Tamini et al., 1999). According to the Brazilian Institute of Floriculture (IBRAFLOR, 2007), the Brazilian floriculture generates approximately US$ 1.2 billion a year. In the State of São Paulo, there are 784 producers of cut flowers, who cultivate a 2,692.20 ha area (São Paulo, 2008). Much of this production is near the city of Campinas, and highlight the cities of Atibaia, with 182 producers and 553.9 ha of planted area, Bragança Paulista, with 49 producers and 341.2 ha of planted area, and Holambra with 47 producers and 180.3 ha of planted area.

The cultivation of roses has the potential to receive irrigation with effluents from sewage treatment plants, due to their high commercial value and presence in highly populated regions, where there is a great volume of sewage. That would generate an economic return and would diminish the impact of releasing sewage into water bodies.

Therefore, the objective of this study was to evaluate the irrigation of roses with anaerobic filter and intermittent sand filter (nitrified effluent) effluents and compare the results with the ones obtained with traditional cultivation. The evaluation of the research was based on the crop productivity and the supply of macronutrients (nitrogen, phosphorus and potassium) in relation to the fertilization requirements of the crop.

Material and Methods

The experiment was installed in a greenhouse located in the city of Campinas, State of São Paulo, Brazil. The geographical coordinates of the place are 22° 49' south latitude, 47° 03' west longitude and altitude of 617 m. According to CEPAGRI (Brazilian Meteorological and Climatic Research Center Applied to Agriculture), the annual average air temperature was 22.4 °C, with average rainfall of 1424.5 mm $year^{-1}$ and relative air humidity between 47 and 73%.

The raw sewage used came from an area in the surroundings of the University campus. A portion of the flow was captured from a point of the pipeline through which the wastewater comes out. The sewage was directed to four anaerobic filters built in stainless steel cylindrical containers with a total capacity of 500 L, operated with upflow and nominal hydraulic retention time of 9 h. The filling material adopted was composed of bamboo rings of the *Bambusa tuldoides* species, with 4 cm of diameter and 5 cm of length.

The effluent from these reactors was applied on the surfaces of four sand filters at the rate of 300 L m^{-2} d^{-1}, at 50 L m^{-2} loads, evenly distributed throughout the day. Some characteristics of the anaerobic and nitrified effluents are presented in Table 1.

The roses were grown in a greenhouse of the Arch type, with a transparent cover made of low-density polyethylene, with 0.15 mm thickness and with protection against UV rays and light diffuser. The dimensions of the greenhouse were: 16.0 m width, 36.0 m length and 4.5 m maximum ceiling height, occupying a total area of 576 m^2.

The crop chosen for this study was *Rosa* sp., of the *Ambiance* variety. The crop was transplanted into beds (portions) with 0.15 m spacing between plants, amounting to 16 plants in each row. Each bed was composed of 3 rows spaced 1.20 m apart.

The experimental design was in randomized blocks, with 6 treatments and 4 replications, amounting to 24 portions:

T1: tap water without conventional fertilization (W);

T2: tap water with conventional fertilization (W+F);

T3: anaerobic effluent without conventional fertilization (AE);

T4: anaerobic effluent with conventional fertilization (AE+F);

T5: nitrified effluent without conventional fertilization (NE); and

T6: nitrified effluent with conventional fertilization (NE+F)

The comparison between treatments was performed through the analysis of variance by the F-test ($p < 0.05$) and comparison of means by the Tukey test ($p < 0.05$).

Table 1. Characteristics of the anaerobic effluents and sand filter used in the experiment

	TKN	NH_4- N	NO_3^--N	P	BOD	Na	K	pH	SAR
	(mg L^{-1})								(mmol L^{-1})$^{0.5}$
Anaerobic effluent	50	48.2	0.9	2.0	159	50	15	6.9	3.4
Nitrified effluent	25	23.5	32.5	1.6	37	56	167	6.7	4.2

* Sodium adsorption ratio

The irrigation system was composed of two reservoirs with 1000 L. In the first reservoir, the anaerobic effluent from the anaerobic filters was stored. In the second reservoir, the effluent from the intermittent sand filters was stored. From these two reservoirs, effluents were pumped to the irrigation boxes, with a capacity of 320 L each. A third box was filled with supply water from the city of Campinas.

In each bed, three lines of dripper tube were installed with eleven emitters with flow rate of 1.15 L h^{-1}. At one bed of each treatment, two tensiometers in the central part were installed, one at the depth of 0.10 m and the other at 0.30 m, located 10 cm from the dripper tube. The tensiometers were read every two days.

Irrigation was conducted according to the water requirements of the crop, keeping the tension of water in the soil near to -10 kPa, as recommended by Casarini et al. (2007) for roses.

The textural analysis of the soil was performed, which presented on average 33% of clay, 14% of silt and 53% of sand, making it possible to classify it as sandy clay. Field capacity (0.1 bar) was 26.13 g g^{-1}, and the permanent wilting point (15 bar) was 17.18 g g^{-1}.

Liming and fertilization were performed according to the recommendations of Malavolta et al. (2002) for the second year of rose cultivation. The dose of limestone was 150 g m^{-2}, applied to the planting line on 13/August/2010. The NPK fertilization needed for the second year was 150, 150 and 180 kg ha^{-1}, divided in four portions of 37.5; 37.5 and 45 kg ha^{-1}. The first portion was done on 18/August/2010 and the second one on 14/October/2010. The fertilizers used were: ammonium sulfate, single superphosphate and potassium chloride. Lime was applied to all beds and fertilizing was performed only in the beds where the treatment contained conventional fertilization.

Regarding productivity, the number of stems produced, stem length (SL), stem diameter (SD), flower bud diameter (BD), flower bud length (BL) and fresh weight of the flower buds (FWB) were evaluated, according to Casarini (2000). The SD, BD and BL were measured with caliper rule. The SD was measured at half length of the stem. The BD was measured in the wider region near the base. The SL measurement was done from the cut point up to the apex of the bud with a ruler.

Results and Discussion

The period of this study was between the months of June and November 2010. Most of the time, irrigation was done four times a week, with three applications of 10 min in the morning. Occasionally, four applications were done in the periods that required more water, monitored through tensiometers.

In Table 2, a summary of the periods of application and the amount of water and effluents applied in the treatments with effluents (NE, NE+F, AE and AE+F) is presented. The alternation between irrigation with water and effluents occurred because of problems at the sewage treatment plant, which did not work during some periods. In the treatments with tap water (W and W+F), the amount of water applied matched the total amounts shown in Table 2. The calculation of the irrigation depth was done considering the area of soil wetted by the dripper tube, approximately 25 cm in width, for an emitter with a flow rate of 1 L h^{-1} during one hour of irrigation in a soil with a sandy clay texture, according to the results of Maia et al. (2010).

The depths applied in this work, on average 5.5 mm d^{-1}, were 57% greater than those obtained by Casarini (2000) in the most productive treatments. This author applied 3.5 mm d^{-1} when cultivating roses of the *Osiana* variety. Such a difference can be justified by the fact that Casarini (2000) kept the matric potential in the soil between -25 and -29 kPa, while in this work, the potential was kept close to -10 kPa.

Cavalcante Júnior (2007), when cultivating roses of the *Iracema* variety in the State of Ceará, obtained the maximum productivity with 7.2 mm d^{-1} depth, which is 31% greater than the one obtained in this experiment.

Considering that the amount of nitrogen in both effluents is approximately 50 mg L^{-1} and the amount of phosphorus is 2 mg L^{-1} (Table 1), and that the volume of effluent applied to each bed during the period from 28/June to 27/November (152 days) was 834.91 L, the amount of nutrients supplied was 42 g N and 1.7 g P per bed in 152 days. This is equal to 137 kg N ha^{-1} $year^{-1}$ and 6 kg P ha^{-1} $year^{-1}$. Even though there was a discontinuity in the use of effluents, the amount of nitrogen applied via effluent was 91% of the crop requirement. The amount of P provided by the effluents was very small, corresponding to 3.5% of the crop requirement.

In the case of potassium, the effluents were quite different, as potassium bicarbonate was added to the sand filter to prevent the pH from decreasing too much and impair the nitrification. Therefore, the nitrified effluent showed a high concentration of K, with an average of 167 mg L^{-1} (Table 1). Thus, the amount of K applied to the soil by the nitrified effluent was 191 kg ha^{-1} in 152 days, or 460 kg ha^{-1} $year^{-1}$, which corresponds to 2.5 times the crop requirement. When considering the anaerobic effluent, the amount of K applied to the soil was 41 kg ha^{-1} $year^{-1}$, which corresponded to 23% of the crop requirement.

Table 2. Amount of water and effluents applied during the experiment

Period	Source of water	Number of days of the period	Volume applied/ bed (L)	Depth applied in the period (mm)	Average depth applied (mm d^{-1})
28/Jun-20/Jul	Water	22	228	112	5.1
21/Jul-26/Jul	Effluent	6	76	37	6.2
27/Jul-20/Aug	Water	25	266	131	5.2
21/Aug-08/Sep	Effluent	19	190	94	4.9
09/Sep-01/Oct	Water	23	228	112	4.9
02/Oct-28/Oct	Effluent	27	335	166	6.1
29/Oct-08/Nov	Water	11	127	62	5.6
09/Nov-27/Nov	Effluent	19	234	116	6.1
Total		152	1682	831	
Water			848	419	
Effluent			835	412	

If no interruptions had happened in the effluent application, the total applied would have been 1682.46 L per bed in the period of 152 days. Thus, the amounts of N, P and K added to the soil would have been 276, 11 and 924 kg ha^{-1} $year^{-1}$, with K calculated considering the nitrified effluent. In this situation, the amount of N provided would be 84% greater than the crop requirement, and the amount of K would be five times greater. When considering the anaerobic effluent, the amount of K added would be 84 kg ha^{-1} $year^{-1}$, which is 47% of the crop requirement. The amount of P provided would increase to 7% of the crop requirement, which is still very low.

Thus, as in Gomes et al. (2009), who worked with sugarcane, the use of effluents without interruption would supply completely the crop requirement regarding nitrogen. It would also be considerably greater than the 195 kg ha^{-1} $year^{-1}$ of nitrogen added to the soil reported by Jimenez (2005) with irrigation with effluents in Tula Valley (Mexico). With respect to phosphorus, the effluent was poor, providing only 13.5% of what was observed by Jimenez (2005), which is 81 kg ha^{-1} $year^{-1}$ of phosphorus.

In Table 3, the amount of stems harvested in the different treatments is shown, which are related to a population of 16 plants contained in a 2.4 m line during a period of 152 days.

It can be observed that the highest yields were in the treatments with the anaerobic effluent (T3 - AE), nitrified effluent (T5 - NE), and (T2 - W+F), with a production of 52, 54 and 32 stems, respectively. Such results follow the same trend as the ones obtained by Marinho et al. (2013), who analyzed roses up to 18 months after planting. In their work, the averages of all treatments with effluents did not differ statistically between themselves and were higher than the averages of the treatments with tap water.

This shows that irrigation with effluents was a substantial source of nutrients for the roses. So, effluents can replace conventional fertilization as a source of nutrients, providing savings in the use of mineral fertilizers. Similar conclusions were obtained by other authors, like Rego et al. (2005), who cultivated watermelon, obtaining an increased productivity through the irrigation with treated sewage equivalent to the control treatment (water+fertilization). Other studies associated effluent irrigation to reduced conventional fertilization and also obtained yields equal to or greater than the control treatment (water + fertilization), like Segal et al. (2011), when irrigating two varieties of olive trees with treated sewage, and Vasquez-Montiel et al. (1996), in a study with corn. Also Freitas et al. (2012), in a research with sunflowers, observed that irrigation with the effluent from a stabilization pond presented a significant advantage in relation to well water for the following parameters of the plant: average height of plants, stem diameter, number of leaves, and diameter of the head.

In addition to the source of nutrients, irrigation with effluents has the advantage of providing nutrients along the productive period of the plant. This decreases the probability of loss of nutrients by leaching, as in conventional fertilization, in which large quantities of fertilizers are used in a single application.

With respect to the parameters of floral stems, there was no statistical difference among the treatments (Table 4), as observed by Marinho et al. (2013). Parameters BD and BL were approximately 31 and 43 mm, respectively. These values were very close to the ones obtained by Marinho et al. (2013), of 33 and 45 mm, who studied the first production cycle of roses.

These same parameters were evaluated for another rose species by Casarini et al. (2007), who applied different amounts of nitrogen and potassium. There was little variation in the parameters. In the first harvest, only BL differed statistically with doses of nitrogen and FWB with interaction between doses of nitrogen and potassium. But in the second harvest, these parameters did not differ, while SL differed.

Rodrigues et al. (1999), studying plastic coverage in hydroponic cultivation of two varieties of rose, found that the increase in production in the cultivation with covered substrate did not alter the average weight of the flowers or the length of the stem. Therefore, such studies show that the characteristics of floral stems do not vary consistently with changes in nutrient availability and substrate moisture. The best growing conditions in nutritional terms resulted in an increase in the number of stems rather than in the size of stems and flower buds.

Table 3. Productivity of floral stems in the different treatments

	Treatments					
	T1 (W)	T2 (W+F)	T3 (AE)	T4 (AE+F)	T5 (NE)	T6 (NE+F)
n. of Stems	21 a	32 ab	52 b	21 a	54 b	28 ab

*Averages with the same letter do not statistically differ between themselves by the Tukey test ($p < 0.05$)
T1 (W) - tap water without conventional fertilization; T2 (W+F) - tap water with conventional fertilization; T3 (AE) - anaerobic effluent without conventional fertilization; T4 (AE+F) - anaerobic effluent with conventional fertilization; T5 (NE) - nitrified effluent without conventional fertilization; T6 (NE+F) - nitrified effluent with conventional fertilization.

Table 4. Average values of the parameters of floral stems

Parameters	Treatments					
	T1 (W)	T2 (W+F)	T3 (AE)	T4 (AE+F)	T5 (NE)	T6 (NE+F)
SL (cm)	32 a*	33 a	35 a	33 a	33 a	35 a
SD (mm)	3.2 a	3.1 a	3.4 a	3.3 a	3.1 a	3.4 a
BD (mm)	30 a	30 a	32 a	31 a	31 a	31 a
BL (mm)	42 a	42 a	43 a	42 a	43 a	44 a
FWB (g)	8.9 a	8.8 a	10.3 a	9.7 a	9.9 a	10.4 a

*Averages with the same letter do not statically differ between themselves by the Tukey test ($p < 0.05$)
T1 (W) - tap water without conventional fertilization; T2 (W+F) - tap water with conventional fertilization; T3 (AE) - anaerobic effluent without conventional fertilization; T4 (AE+F) - anaerobic effluent with conventional fertilization; T5 (NE) - nitrified effluent without conventional fertilization; T6 (NE+F) - nitrified effluent with conventional fertilization.

Conclusions

1. The use of effluents was a good source of nitrogen and an insufficient source of phosphorus, with irrigation guided by the water requirements of the crop.

2. The anaerobic effluent was a reasonable source of potassium and the nitrified effluent provided excess potassium.

3. The production of floral stems was higher in treatments with effluents without conventional fertilization.

4. The parameters of the floral stems stem length, stem diameter, flower bud diameter, flower bud length and fresh weight of the flower buds did not differ among treatments.

Literature Cited

Carey, R. O.; Migliaccio, K. W. Contribution of wastewater treatment plants effluents to nutrient dynamics in aquatic systems: a review. Environmental Management, v.44, p.205-217, 2009. http://dx.doi.org/10.1007/s00267-009-9309-5

Casarini, E. Manejo da irrigação na cultura da roseira cultivada em ambiente protegido. Piracicaba: ESALQ/USP, 2000. 62p. Dissertação Mestrado

Casarini, E.; Folegatti, M. V.; Silva, E. F. F. Produtividade da roseira em função de doses de nitrogênio e potássio aplicadas via fertirrigação em ambiente protegido. Magistra, v.9, p.250-256, 2007.

Cavalcante Júnior, J. A. H. efeitos de níveis de irrigação na cultura da roseira variedade "iracema" cultivada em ambiente protegido. Fortaleza: UFC, 2007. 59p. Dissertação Mestrado

Freitas, C. A. S.; Silva, A. R. A.; Bezerra, F. M. L.; Andrade, R. R.; Mota, F. S. B.; Aquino, B. F. Crescimento da cultura do girassol irrigado com diferentes tipos de água e adubação nitrogenada. Revista Brasileira de Engenharia Agrícola e Ambiental, v.16, p.1031-1039, 2012. http://dx.doi.org/10.1590/S1415-43662012001000001

Gomes, T. M.; Melfi, A. J.; Montes, C. R.; Silva, E.; Sundefeld Júnior, G. C.; Deon, M. D.; Pivelli, R. P. Aporte de nutrientes e estado nutricional da cana-de-açúcar irrigada com efluente de estação de tratamento de esgoto com e sem desinfecção. Revista DAE, v.180, p.17-23, 2009.

IBRAFLOR - Instituto Brasileiro de Floricultura. In: Floricultura no Brasil: Apontamentos mais relevantes sobre o papel sócio-econômico recente da atividade. 2007. <http://www.ibraflor.org/userfiles/file/Balana%20Comercial%20Floricultura%202007.pdf> 9 Jul. 2009.

Jimenez, B. Treatment technology and Standards for agricultural wastewater reuse: a case study in México. Irrigation and Drainage, v.54, p.S23-S33, 2005. http://dx.doi.org/10.1002/ird.183

Maia, E. C.; Levien, S. L. A.; Medeiros, J. F. de; Dantas Neto, J. Dimensões de bulbo molhado na irrigação por gotejamento. Revista Ciência Agronômica, v.41, p.149-158, 2010.

Malavolta, E.; Gomes, F. P.; Alcarde, J. C. Adubos e adubações. São Paulo: Nobel, 2002. 200p.

Marinho, L. E. O.; Tonetti, A. L. ; Stefanutti, R. ; Coraucci Filho, B. Application of reclaimed wastewater in the irrigation of rosebushes. Water, Air and Soil Pollution, v.224, p.1669-1676, 2013. http://dx.doi.org/10.1007/s11270-013-1669-z

Qadir, M.; Wichelns, D.; Raschid-Sally, L.; Mccornick, P. G.; Drechsel, P.; Bahri, A.; Minhas, P. S. The challenges of wastewater irrigation in developing countries. Agricultural Water Management, v.97, p.561-568, 2010. http://dx.doi.org/10.1016/j.agwat.2008.11.004

Rego, J. L.; Oliveira, E. L. L.; Chaves, A. F.; Araújo, A. P. B.; Bezerra, F. M. L.; Santos, A. B.; Mota, S. Uso de esgoto doméstico tratado na irrigação da cultura da melancia. Revista Brasileira de Engenharia Agrícola e Ambiental, v.9 (sup), p.155-159, 2005.

Rodrigues, E. J. R.; Minami, K.; Farina, E. Cobertura do substrato com filme plástico e o cultivo hidropônico da roseira: Produtividade, consumo de água, temperatura e salinização. Scientia Agricola. v.56, p.785-795, 1999. http://dx.doi.org/10.1590/S0103-90161999000400004

São Paulo. Secretaria de Agricultura e Abastecimento. Coordenadoria de Assistência Técnica Integral. Instituto de Economia Agrícola. Levantamento censitário de unidades de produção agrícola do Estado de São Paulo - LUPA 2007/2008. São Paulo: SAA/CATI/IEA, 2008. <http://www.cati.sp.gov.br/projetolupa>. 15 Jan. 2012.

Segal, E.; Dag, A.; Ben-Gal, A.; Zipori, I.; Erel, R.; Suryano, S.; Yermiyahu, U. Olive orchard irrigation with reclaimed wastewater: agronomic and environmental considerations. Agriculture, Ecosystems and Environment, v.140, p.454-461, 2011. http://dx.doi.org/10.1016/j.agee.2011.01.009

Tamini, Y. N.; Matsuyama, D. T.; Ison-Takata, K. D.; Nakano, R. T. Distribution of nutrients in cut-flower roses and the quantities of biomass and nutrients removed during harvest. Hortscience, v.34, p.251-253, 1999.

Vazquez-Montiel, O.; Horan, N. J.; Mara, D. D. Management of domestic wastewater for reuse in irrigation. Water Science and Technology, v.33, p.355-362, 1996. http://dx.doi.org/10.1016/0273-1223(96)00438-6