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# Constructed wetlands for domestic wastewater treatment in a Mediterranean climate region in Chile

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## Abstract

**Background:** Constructed wetlands are a promising, cheap and effective wastewater treatment in small communities. The studies on these systems have been reported mainly from cold, tropical or subtropical climate regions. In this work we constructed a pilot plant with six horizontal subsurface flow constructed wetlands (HSSF CWs) with a surface area of 2 $m^2$ and a depth of 0.6 m each, planted with *Typha latifolia* or *Scirpus* sp., and filled with gravel (G) or fine gravel (FG) of 2.8 and 1.2 cm of diameter respectively, continuously fed with raw domestic wastewater. This experimental setup was evaluated over 280 days for the removal of organic matter and nutrients in a Mediterranean climate, near Valparaíso, Chile. The removal of total COD, $NH_4^+$-N and $PO_4^{-3}$-P was calculated, in order to assess by analysis of variance the effect of initial pollutants concentration, air temperature (season) and plant/support combination on the wetlands performance.

**Results:** The *Scirpus*/FG combination showed the highest average removal of total COD of about 59%, and *Typha*/FG shows the highest removal of $NH_4^+$-N and $PO_4^{-3}$-P (49 and 32%, respectively). Furthermore, the removal of organic matter was independent of influent concentration, while mildly dependent of the season, unlike nutrients removal that was dependent on these two parameters. Media, plant and the plant/media combination influenced positively organic matter, ammonia and phosphorous removal, respectively.

**Conclusions:** Overall, the results demonstrate the potential of wetlands in treatment of wastewater in Mediterranean regions and show how these can help to improve the quality of water in domestic zones without high-throughput technologies.

**Keywords:** constructed wetlands, domestic wastewater treatment, horizontal subsurface flow system, Mediterranean climate.

## INTRODUCTION

Wetlands are natural or engineered systems used for domestic and industrial wastewater treatments. These systems remove organic matter and nutrients through a combination of biological, physical and chemical phenomena (Stottmeister et al. 2003; Sundaravadivel and Vigneswaran, 2010). Frequently, wastewaters from small communities are discharged without previous treatment into rivers and lakes. The impact of this undesirable anthropogenic negative effect on the ecosystem can be reduced if; organic matter, nitrogen and phosphorous present in these wastewaters are removed before the final discharge into the receiving natural waters. To solve this problem in small communities, constructed wetlands (CW) may represent an efficient and cost-effective technology to improve domestic wastewater quality (Sundaravadivel and Vigneswaran, 2010). This is explained, at least in part, since the operational, maintenance and control costs associated with these systems are lowered in comparison to traditional wastewater systems. Wetlands are not just a simple experimental setup. A wide variety are being installed in the world (Vymazal and Kröpfelová, 2009; Vymazal, 2011). For instance, in Taipei, Taiwan, the government has designed a contingency plan to improve water quality in the Danshui river. Since 2004, 14 CWs had been installed in the river system of the metropolitan Taipei area and the concentration of pollutants has gradually been falling over the last decade (Cheng et al. 2011).

Several studies in this area have been performed, particularly in horizontal subsurface flow (HSSF). These have shown efficiencies over 60% on organic matter removal, depending on the source of wastewaters in the CWs. In HSSF systems, the wastewaters flows slowly through the wetlands, keeping in direct contact the different residues, in a complex aerobic, anaerobic and anoxic zones. Studies of methane emission have shown that methanogenic bacteria and anaerobic processes play important roles in the organic matter degradation (Mander et al. 1997; Vymazal and Kröpfelová, 2009). Within nutrients, the ammonia is mainly removed by plant uptake or by denitrification processes through microbial activity. Nitrification may be limited by oxygen supply, although 30% of ammonia removed in wetlands has been reported by this way (Stottmeister et al. 2003; Tanner and Kadlec, 2003; Vymazal, 2007). Meanwhile, the phosphorous removal mechanisms include plant assimilation, adsorption on the media surface, precipitation and retention in sediments. Adsorption on the media surface has been considered the main mechanism for phosphorous removal. The removal of this kind of contaminants in CWs varies between 30-60%, depending on the wastewater and the media used (Vymazal, 2007; Cui et al. 2008).

Previous studies have shown that organic matter removal in wetlands is relatively independent of air temperature. However, temperature fluctuation may affect wetland operation, since nutrient assimilation by plant and bacterial activity, among other important removal mechanisms in wetlands, decrease with low temperatures (Akratos and Tsihrintzis, 2007; Gikas and Tsihrintzis, 2010). Consequently, a season-dependent removal efficiency of nutrients may be expected in wetlands. Despite the progress in CWs operation, the studies on these systems have been reported mainly from cold, tropical or subtropical climate regions (Vymazal, 2011). In these areas, daily temperature fluctuation are lower than in those regions possessing a Mediterranean climate, and therefore, it is not possible to assess the influence of daily temperature fluctuation on the removal of organic matter and nutrients.

In this study, we evaluate the operation of a pilot plant constructed with six HSSF CWs during the four seasons for the treatment of domestic wastewater in order to estimate the stability of different plant/support combination taking in consideration organic matter, ammonia and phosphorous removal. This plant was built out in Valparaíso, Chile, a Mediterranean zone in the central region of the country. Wetlands planted with *Scirpus* sp or *Typha latifolia* and filled with gravel or fine gravel were compared, based on removal efficiency data of organic matter, and nutrients, using proper statistical analysis.

## MATERIALS AND METHODS

### Pilot plants description

As shown in Figure 1, the pilot plant consist in a set up of six CWs, 2 m long each, 1 m wide and 0.6 m deep. Raw domestic and industrial wastewater were collected in a central distribution tank, and fed to the six CWs in parallel. A main pipe feeds simultaneously all the wetlands, and each one has a feeding valve that independently regulates the input stream flowing. An adjustable volume shaped floodgate located at the exit of each wetland regulates its water level and the outlet flow. The combination of plant and media in the CWs was chosen in order to evaluate the influence of two macrophytes, *Typha latifolia* and *Scirpus* sp, and two media, gravel (G) and fine gravel (FG) of 2.8 and 1.2 cm of diameter, respectively. The initial porosity for (G) and (FG) bed was 0.47 and 0.42 respectively. The average influent flow rate to each wetland was 0.3 $m^3 d^{-1}$ and the average wastewater quality was 200 mg $COD_{total}$ $l^{-1}$, 95 mg $COD_{Filtered}$ $l^{-1}$, 37 mg $NH_4^+$-N $l^{-1}$ and 33 mg $PO_4^{-3}$-P $l^{-1}$.

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The results shown in this study correspond to CWs operation carried out by 280 days. Initial plant density in wetlands planted with *T. latifolia* and *Scirpus* sp were 33 and 19 plants $m^{-2}$, respectively. A synthetic wastewater that imitates the quality of domestic wastewater was fed to the wetlands during 125 days, before the beginning of the experiment. After this acclimatization period, raw domestic wastewater was continuously fed to the wetlands over 280 days at an average flow of 12 l/h. The maximum and minimum load of organic matter, ammonia and phosphorous were 503 and 144, 130 and 42, 18 and 9 Kg $ha^{-1}$ $d^{-1}$, respectively. The hydraulic loading rate was 0.114 m $d^{-1}$.

### Pollutants analysis

Periodical analysis of chemical oxygen demand COD, $COD_{Filtered}$, ammonia, and phosphorus, were carried out at the pilot plant inlet and outlet stream of each wetland over 280 days since February and removal efficiency were measured and calculated from these data. Since the experiment included all the four seasons, removal efficiencies were assessed under different climatic conditions. The temperature average for each season was: summer +17.7ºC, autumn +11.2ºC, winter 10.5ºC and spring 12.5ºC. Standard methods were used for chemical analysis of pollutants (APHA, 1992).

### Statistical analysis

In order to compare the pollutants removal efficiency, an analysis of variance was carried out using the Fisher's Least Significant Difference method. The effect of raw wastewater pollutants concentration, seasons, and the plant/media combination on the pollutants removal was assessed independently. The application of the Fisher method consists of grouping the compared systems based on the contrasting of a response variable. In our study, the response variables are the organic matter, ammonia or phosphorous removal, and the compared systems are the wetlands. In order to analyze the effect of pollutants concentration in the wastewater, data were divided in three ranges, low, medium and high by a percentile analysis. Table 1 show the ranges for organic matter, ammonia and phosphorus.

**Table 1. Determined ranges for each pollutant concentrations (mg/l).**

| | Low | Medium | High |
|---|---|---|---|
| **COD** | 100 - 167 | 167 - 192 | 192 - 349 |
| **$NH_4^+$-N** | 29 - 39 | 39 - 58 | 58 - 90 |
| **$PO_4^{-3}$-P** | 6.4 - 8.5 | 8.5 - 11 | 11 - 12.2 |

## RESULTS AND DISCUSSION

### Organic matter removal

Pilot plant inlet and outlet stream of total COD concentration are shown in Figure 2. During the first 150 days of wetlands operation, the outlet average of total COD concentration was lower than 50 mg $l^{-1}$. This period correspond to the summer and autumn seasons. From day 150, in winter, when high temperature fluctuation occurred during the day, total COD concentration in the outlet stream started to increase. The season affected slightly total COD removal ($p$ < 0.1). When removal data were compared for each season, three groups were observed: winter/spring, autumn and summer, with an average removal of 43, 65, 54%, respectively (Figure 3a).The highest COD removal was achieved during autumn, in *Scirpus*/G configuration, reaching on average of 78%. During this period, temperature fluctuations during the day are low (Figure 3c). The group winter/spring showed the lowest total COD removal, potentially due to the decrease in daily average temperatures (Akratos and Tsihrintzis, 2007; Vymazal and Kröpfelová, 2009). The recovery of wetlands removal capacity after low winter temperatures was not reached in spring. During winter, the plant density of those wetlands planted with *Typha* decreased from 127 to 94 plants $m^{-2}$ (26% reduction) and those with *Scirpus*, decreased from 600 to 300 plants $m^{-2}$. This drastic 50% reduction in plant density could be due to the low ambient temperature, achieving the lowest temperature (-6ºC) during the whole analyzed period. These results indicate that plants do not play a central role in COD removal since their reduction is not directly proportional to the COD levels reduction. In this regard, during the whole analyzed period representing all-four seasons, similar COD level trends were observed. Thereby, these results support previous conclusions and results, strongly suggesting that bacteria may play a key role in the removal of total COD in HSSF CWs (Akratos and Tsihrintzis, 2007; Camacho et al. 2007; Vymazal and Kröpfelová, 2009).

Removal of organic matter was not affected by the influent concentration of contaminants, with a total COD in the range between 100 and 349 mg $l^{-1}$ ($p > 0.1$) (Table 1). Removal data were grouped into an average value of 52% (Figure 3b). This indicates that when organic matter varied within these ranges, total COD removal was constant and therefore there is a load fluctuation tolerance in HSSF CWs (Caselles-Osorio et al. 2007; Sun and Cooper, 2008; Vymazal and Kröpfelová, 2009).

In average, total COD removal in un-planted/G was 53% in comparison with CW without media, which showed a 36% (Figure 3c). These results indicate that some mechanisms, mainly related to the presence of media, are relevant for COD removal. Putatively, biofilm activity or the amount/composition of bacteria attached to the media in un-planted wetlands is larger or more important than those observed in planted wetlands.

Analysis of variance confirmed that total COD removal did not depend on the plant/media combination in wetlands ($p < 0.1$) (Figure 3c). Two groups among wetlands were observed. First, the *Typha*/non media group with 36% of total COD removal, and the second, composed of *Typha*/FG, *Typha*/G, *Scirpus*/G, un-planted/G and *Scirpus*/FG wetlands with 55%. This result clearly indicates that plants do not influence total COD removal, in agreement with previous observations (Akratos and Tsihrintzis, 2007). The results obtained with the *Typha*/non-media wetland suggested that the media component is crucial for COD removal, and that the bacterial activity may be responsible of COD removal in wetlands (Stottmeister et al. 2003). Thus, media may provide an appropriate surface for biofilm formation, in which bacteria attached, would be the main form of COD removal in the Mediterranean's HSSF CWs.

## Ammonia removal

Wetlands influent and effluent ammonia concentrations are shown in Figure 4. Ammonia removal data in wetlands is summarized in Figure 5c, where *Typha*/non-media and *Scirpus*/G had the highest removal percentage during summer (about 90%). In this season, increased nutrient uptake is expected due to maximum temperatures and higher plant density, which in turn activates ammonia removal by the development of biofilms in plant roots. In addition, higher nitrifying activities are also expected in planted wetlands than in those un-planted systems (Bigambo and Mayo, 2005; Akratos and Tsihrintzis, 2007). Interestingly, during autumn and in contrast with the summer season, higher removal efficiencies were achieved in *Typha*/FG, *Typha*/G, and Scirpus/FG. The same observation can be concluded when the winter period is compared to spring, in all conditions. This leads to the conclusion that there is no direct correlation in ammonia removal between temperature and plant biomass, and therefore, in each CWs, removal depends on each season characteristics and configurations.

Statistic analysis showed that the seasons affect ammonia removal in wetlands in Mediterranean climate ($p < 0.1$). Seasonal data of ammonia removal were grouped in Figure 5a as follows: summer/autumn (63%), winter (27%) and spring (6%). Low temperature, as mentioned, could explain the observed decrease due to plant density and/or activity reduction in wetlands. The highest ammonia removal was achieved in summer/autumn, when lowered temperature fluctuations during the day and higher plant biomass were observed. It has been reported that temperature promotes plants growth, increasing nitrogen uptake (Akratos and Tsihrintzis, 2007). Nevertheless, it is not always a rule, explaining at least in part our results. In artificial wetlands planted with *Phragmites australis* or *T. latifolia,* higher temperatures did not enhance nitrogen removal, suggesting that other factors may influence nutrients removal (Durán-de-Bazúa et al. 2008).

Ammonia removal was dependent on the influent ammonia concentration ($p < 0.1$) in the range between 29 and 90 mg $l^{-1}$ (Table 1). The analysis of variance formed two groups: high and low/medium concentration, with average ammonia removal of 6% and 43%, respectively (Figure 5b). When influent concentration increased, ammonia removal decreased. Inhibition of plant assimilation or nitrifying bacteria activity at high concentration could explain this decrease. Saturated water and lower oxygen conditions favour nitrogen removal through a process less efficient as denitrification (Albuquerque et al. 2009; Canga et al. 2011).

Removal of ammonia in un-planted/G was always lower than 30%. Compared to the other wetlands, the un-planted wetland showed the lowest ammonia removal during all seasons. During autumn, in wetlands without media, ammonia removal was similar to those with media. During summer, ammonia removal in non-filled wetlands was greater than CWs *Typha*/Gor *Typha*/FG and was similar to *Scirpus*/G (Figure 5c). These results indicate the importance of plant for ammonia removal. A positive effect of media could be observed to lower temperatures in winter and spring when plants were decreased. This implicated a rise of ammonium removal in *Typha*/Gand *Typha*/FG in contrast to *Typha*/non-media. The use of porous media could activate aeration process and hence nitrification process in low temperatures (Akratos and Tsihrintzis, 2007; Forbes et al. 2010).

When the ammonia removal was analyzed by the plant/media combination ($p < 0.1$), wetlands were divided into three groups (Figure 5c). In the first group, only un-planted/G appears with an average ammonia removal of 18%. The second group, *Typha*/non media, *Typha*/G, and *Scirpus*/FG showed a 42%, and the third group formed by wetlands *Typha*/FG and *Scirpus*/G had a 47% of ammonia removal. Media type did not influence removal, since wetlands with different media were grouped together. Ammonia removal was independent of the type of plant, since wetlands planted with *Typha* (*Typha*/FG) and Scirpus (*Scirpus*/G) formed a single group. The role of plants in ammonia removal was clear when data from planted and un-planted wetlands were compared. In all planted wetlands the removal was higher than 39%, as opposed to un-planted wetlands in which only an 18% was reached. Direct and indirect process may explain the positive influence of plants in the removal. The direct process mainly involves plant assimilation or uptake of ammonia, and the indirect one refers to the supply of oxygen by plant roots for nitrification process (Vymazal, 2007; Bezbaruah and Zhang, 2009).

## Phosphorous removal

Wetlands influent and effluent ammonia concentration are shown in Figure 6. Data of phosphorous removal for each wetland is summarized in Figure 7c. Average removal of phosphorous during each season is presented in Figure 7a, with the highest and lowest removal in summer (43%) and spring (-6%), respectively.

The seasonal variations strongly affected the phosphorous removal in HSSF CW ($p < 0.1$). Seasonal data formed three groups: summer/autumn with a removal of 40%, winter with 2% and spring with -6% (Figure 7a). Phosphorous removal decreased during winter, probably due to the decrease in plant density. Death plants may be an additional source of phosphorous and could explain the negative removal observed in spring. It has been confirmed that plant uptake is the second most important mechanism of phosphorous removal, so, a larger plant growth during summer/autumn improved its removal, while cold seasons such as winter/spring it diminished (Stottmeister et al. 2003; Akratos and Tsihrintzis, 2007; Vymazal, 2007; Villaseñor et al. 2011).

Phosphorous removal efficiency was dependent on influent phosphorous concentration in the range between 6.4 and 12.2 mg $l^{-1}$ ($p < 0.1$) (Table 1). Figure 7b shows removal efficiency on three ranges, low, medium and high. Two groups were observed after the analysis of variance. The first group included ranges low and medium, while the other group, the range high, with an average removal of 7% and 16%, respectively. Phosphorous removal increased at higher phosphorous concentration. On the contrary, Shan et al. (2011), found that the removal efficiencies of CWs with plants might be higher when the nutrient load de crease.

When wetlands were compared in their respective plant/media combination, three groups were formed ($p < 0.1$) (Figure 7c). *Typha*/non-media and un-planted/G were the first group with an average phosphorous removal of 3%, *Typha*/G was the second group with 20%, and *Typha*/FG, *Scirpus*/G, and *Scirpus*/FG were the third group with 29%. Since the first group showed the lowest removal and it included the un-planted wetland (5%) and the wetland without media (2%) respectively, the result indicates that plants and media must work together for a better removal of phosphorous nutrients, suggesting a synergistic mechanism. It is known that different porous media through physicochemical mechanisms can improve phosphorous removal, (Vymazal, 2007; Cui et al. 2008). For other hand, plants, mainly through uptake processes, can rise until 40% the removal, or indirectly they can influence positively the growth or activation of microbial removal (Camacho et al. 2007; Shan et al. 2011), thereby then plants as well as the media could improve the removal efficiency, suggesting a synergistic relation of both in phosphorous removal.

## CONCLUDING REMARKS

From the results presented in this work the following conclusions can be drawn:

- Best performance in terms of organic matter, ammonia and phosphorous removal was achieved in *Scirpus*/G.
- Removal of organic matter was independent and stable to influent concentrations in the range 100 to 349 mg $l^{-1}$. Moreover, the results shown to be mildly affected by the seasons, and were independent of the plant/media combination. Media, on the other hand, positively influenced organic matter removal, independent of its size.
- Ammonia removal was dependent on the influent concentration in the range 29 to 90 mg $l^{-1}$, which in turn was affected strongly by the seasons. Moreover, ammonia removal was observed to be plant dependent, while media type positively influenced its removal during cold seasons.
- Phosphorous removal was dependent on influent phosphorous concentration in the range 6.4 to 12.2 mg $l^{-1}$ which in turn was strongly affected by the seasons. Plants and media work synergistically in its removal.

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# Figures

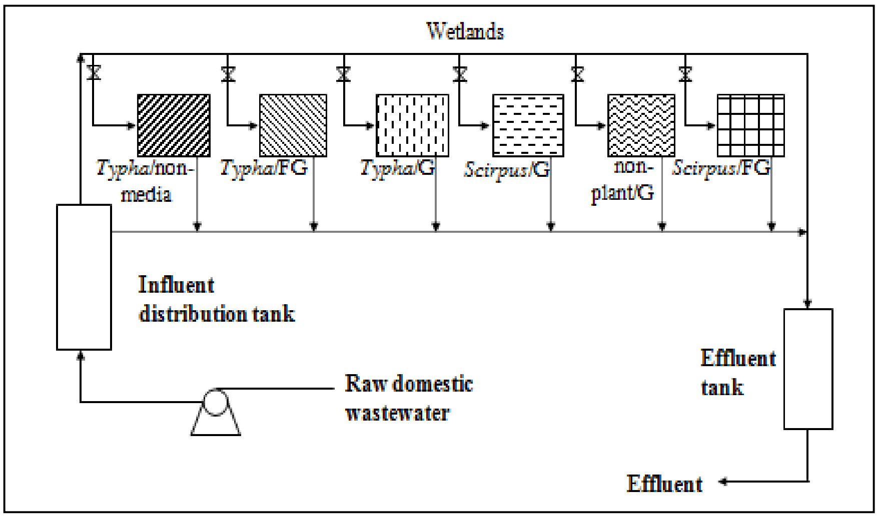

**Fig. 1 Schematic diagram of the pilot plant setup.** Combination of plant and media in wetlands were: *Typha*/non-media, *Typha*/FG, *Typha*/G, *Scirpus*/G, un-planted/G, and *Scirpus*/FG.

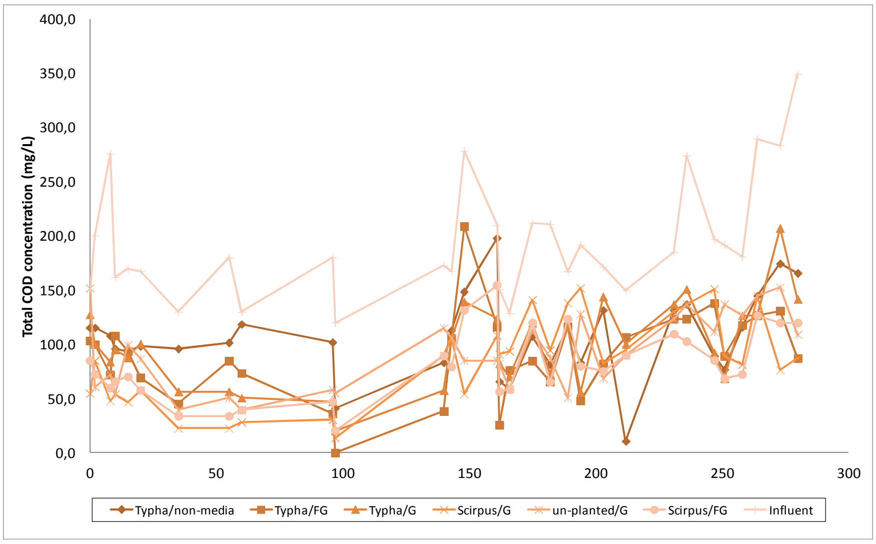

**Fig. 2 Variation of influent and effluent concentration of total COD during the operation period in different wetland configurations.**

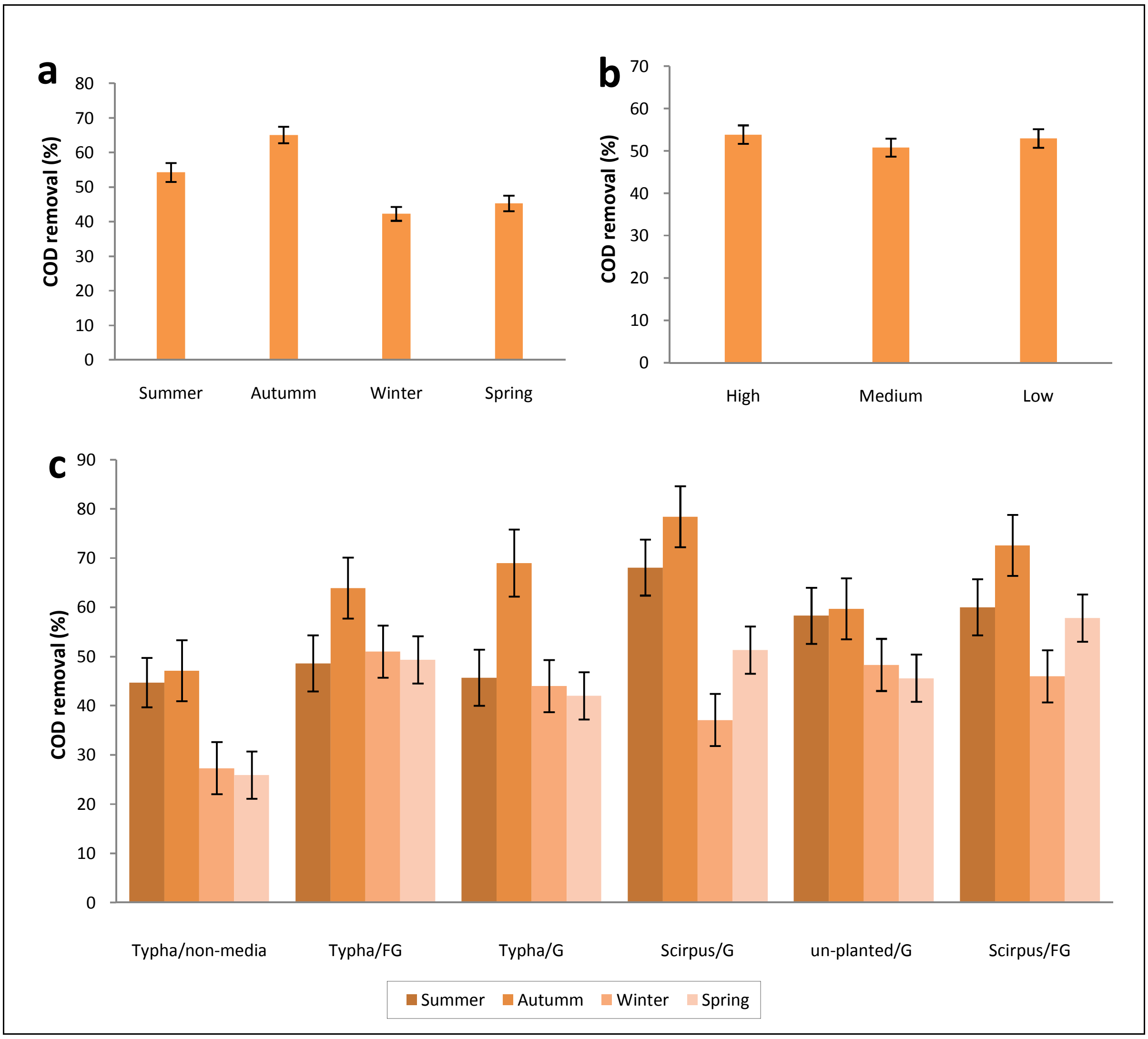

**Fig. 3 Analysis of variance of data of total COD as a function of seasons (a); pollutants concentration (b); and combination plant/media (c).**

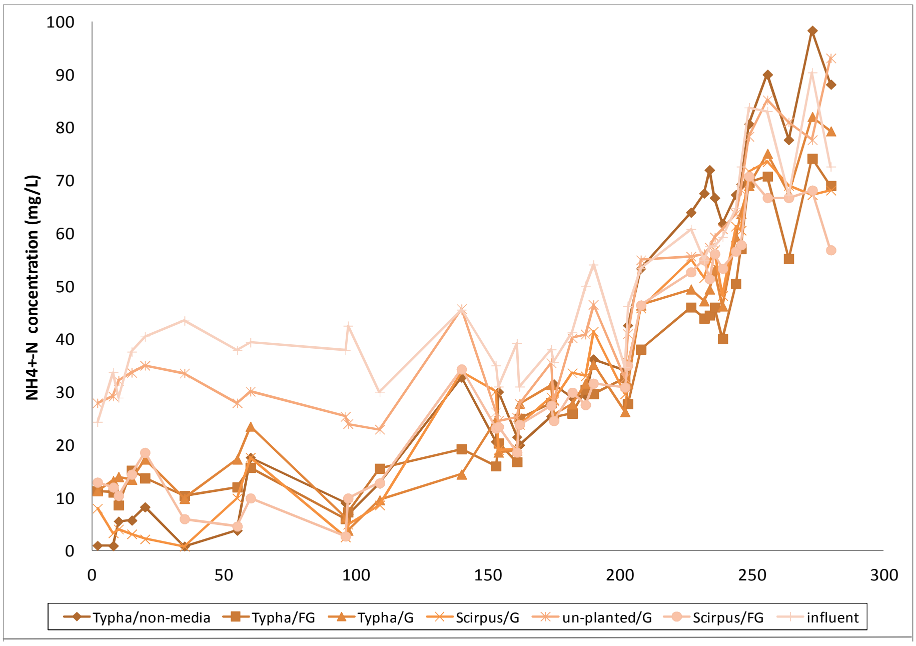

**Fig. 4 Variation of influent and effluent concentration of ammonia during the operation period in different wetland configurations.**

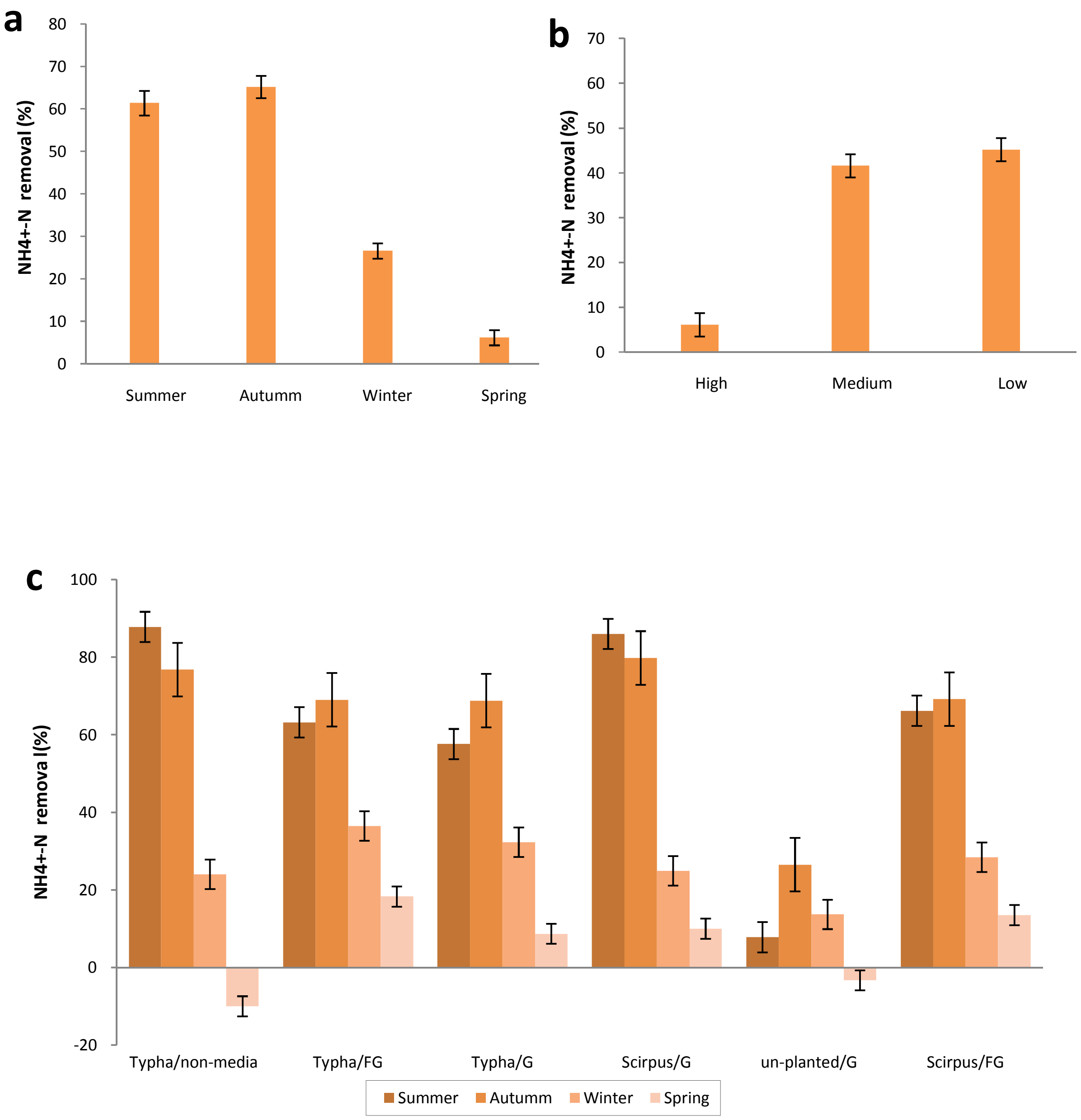

**Fig. 5 Analysis of variance of data of ammonia removal as a function of seasons (a); pollutants concentration (b); and combination plant/media (c).**

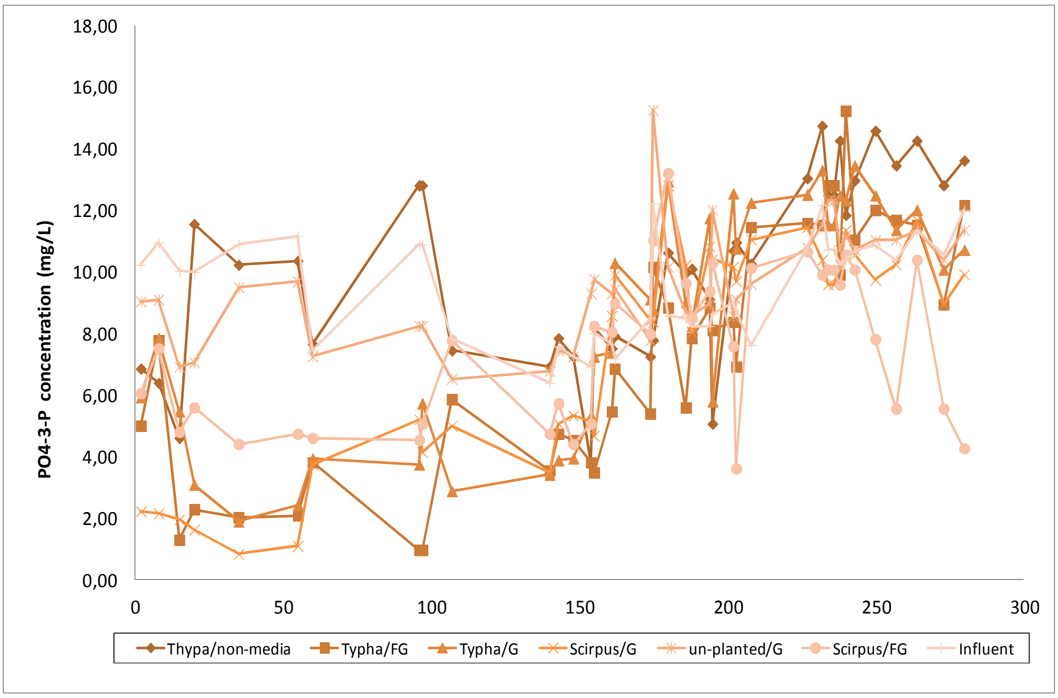

**Fig. 6 Variation of influent and effluent concentration of phosphorous during the operation period in different wetland configurations.**

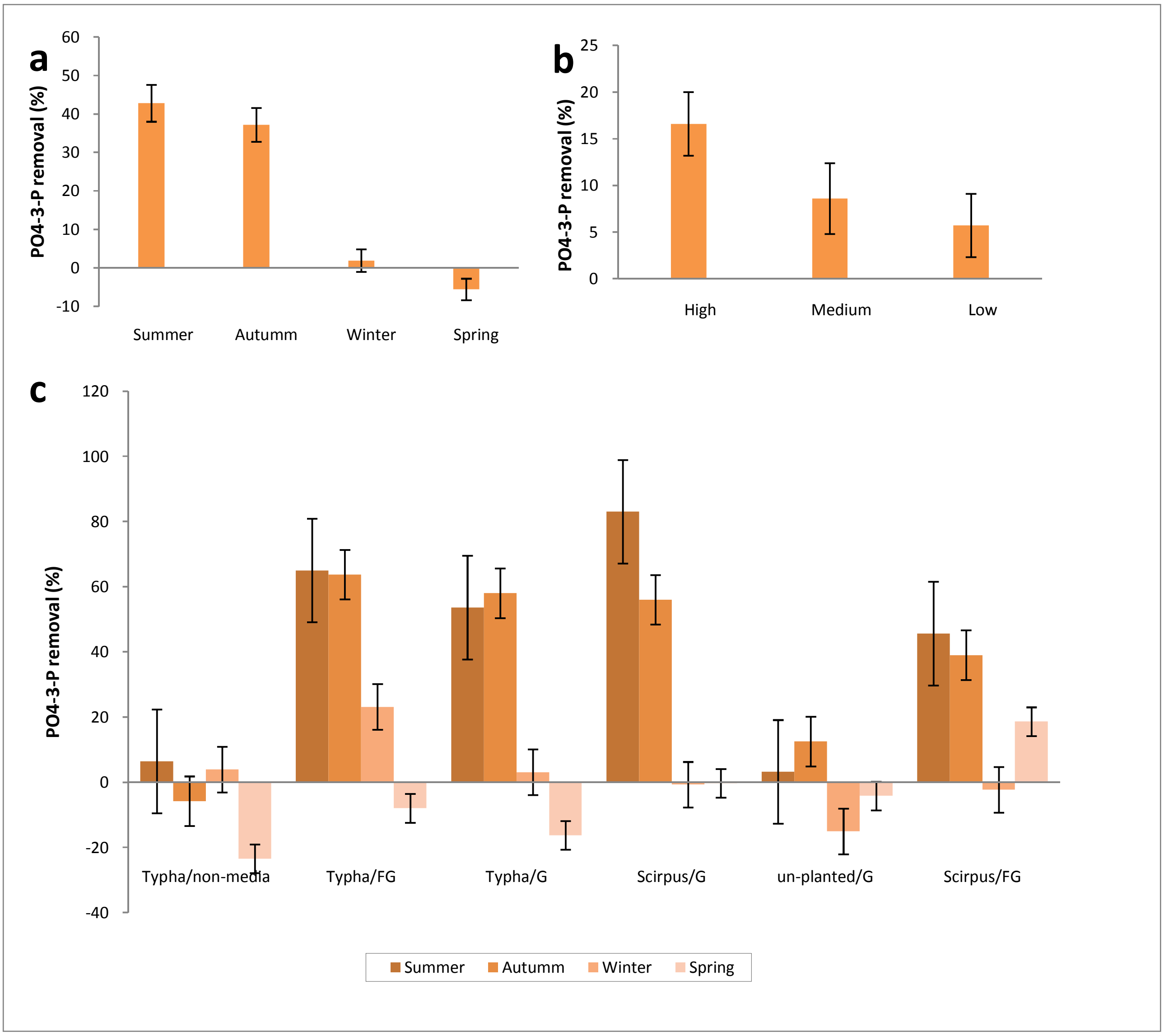

**Fig. 7 Analysis of variance of data of phosphorous removal as a function of seasons (a); pollutants concentration (b); and combination plant/media (c).**