Enhancing the environmental performance of biotrickling filters treating volatile organic compounds in air

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Abstract. The actual biotrickling filtration technology addresses volatile organic compounds (VOCs) removal from air, by their conversion into less harmful gaseous compounds (e.g. carbon dioxide). The actual study extends this capability towards not only VOCs removal, but also removal of carbon dioxide issued from biodegradation, in the same biotrickling filter (BTF). This upgrade results in higher C-capture and the reduction of greenhouses gases associated with this process, thus increasing the environmental performance of such BTFs. The model pollutant used in this study is ethanol, while a co-immobilised microalgae and compost-derived microorganisms is used for the first time accomplishing the above mentioned desiderate (simultaneously removal of VOC and carbon dioxide in the same BTF), under continuous regime and illumination provided by an array of light-emitting diodes (LED)). Very promising performances are obtained, revealing new competitive alternatives with high potential for further development, in the light of atmospheric protection and climate change issues.

1. Introduction
Biological removal of volatile organic compounds (VOCs) is considered a cost-effective alternative to the conventional physical-chemical methods used for air treatment [1]. Biotrickling filters (BTFs), biofilters and bioscrubbers have been intensively studied in this regard. Criteria such as loading rate, elimination capacity and removal efficiency are usually determined to describe the performance of such reactors, along with carbon dioxide production as an indicator of the biological process [2-4]. CO₂ results from VOC bioconversion, as well from other biological activity associated with the particularities of the microbiota involved in the respective bioreactors [3]. On the other hands, CO₂ is a greenhouse gas that should also be addressed in terms of the environmental impact related to global warming and climate changes. Extending the bioreactors capability towards not only VOCs removal, but also removal of CO₂ resulted from the biological process, could increase C-capture and their overall environmental performance. This desiderate could be achieved by using symbiotic microorganisms with specific role (VOCs-degraders and CO₂-consumers) that are able to grow together either in co-immobilised and/or suspended form. Some authors highlight the possibilities and the beneficial role of coupling some microorganisms and microalgae in wastewater treatment systems [5, 6], while the actual study reveals new opportunities and challenges associated with the application for air treatment as well. For example, compost based-microorganisms (VOC-degraders) and microalgae (CO₂-consumers) could be coupled in a suitable reactor such as BTF to achieve this goal.
While the first ones act as CO\textsubscript{2}-suppliers for the microalgae, the last ones act as O\textsubscript{2}-suppliers to compensate some of the oxygen required for the aerobic process [5, 7]. This concept has been for the first time undertaken at the “Gheorghe Asachi” Technical University of Iasi (BIO-SPACE LIFE Laboratory) within the BIO-UP project, and the actual study describes some of the obtained results. As previous studies shows that A. platensis can be used for air revitalization in spacecrafts [8, 9], this type of the microalgae was considered in the actual study as well, along with other more common microorganisms for air biotreatment purposes such as those derived from compost.

2. Materials and methods

2.1. Experimental set-up
Two similar BTFs, consisting in a transparent PVC column of 10 cm diameter, were equipped each one with a 22 cm height of packing bed (polypropylene spheres, Jaeger Tri-Packs) (Figure 1). For each BTF, ethanol-rich air was fed at the bottom of the column using an air pump, in counter-current to the nutrient solution that was recycled at the top using a peristaltic pump. Continuous illumination was provided by LED (array of light-emitting diodes) – based lighting sources that have been located close to the two-opposite sides of the column in order to assure a light intensity of 30Klux /30Klux for the packing bed, which was measured with a digital luxmeter (Extech, Light Meter LT300).

![Figure 1. Experimental set-up](image)

2.2. Analytical methods
Gas analysis was achieved in terms of ethanol, carbon dioxide and oxygen, by using a Micro GC Fusion Gas Analyzer (Inficon, USA) equipped with TCD (thermal conductivity detector), the gas being sampled from ports located before and after BTF. Nutrient solution was regularly checked for pH and DO (dissolved oxygen), by using a HACH multi-parameter device. In addition, nitrate was determined, via using a HACH DR/2010 spectrophotometer and HACH reagents kits.
2.3. Experimental methodology

The two BTFs were prepared as following:
- BTF1 was subject to the immobilisation with indigenous microorganisms derived from compost (by packing bed immersion in a suspension of compost/distilled water supplied with glucose (1g glucose : 100 g compost), followed by acclimatization and co-immobilisation as described below; commercial peat-based compost with active humus was used in this study as a source of microorganisms;
- BTF2 was subject to the immobilisation with microalgae (by packing bed immersion in a suspension of *A. platensis* culture), followed by acclimatization and co-immobilisation as described below; *Arthrospira platensis* PCC 8005, Pasteur Culture Collection, France, was used in this study.

The nutrient solution for BTF1 consisted in a growth medium used for the microorganisms development [10], while a Zarrouk medium [9, 11] free of sodium bicarbonate and sodium chloride was used for BTF2. The initial pH was adjusted to 9.5 in both cases, by using sodium hydroxide. No replace by fresh solution was performed for the entire testing period, but nutrient supply (Zarrouk-based components for both cases) and pH adjustment (when a drop below 9 was noticed) were performed upon request. Also, any evaporated water was compensated by distilled water supply. Thus, for co-immobilisation, the leachate from the acclimatized BTF containing sole compost-derived microorganisms was filled/recycled through the acclimatized BTF containing sole microalgae (for about one hour) and vice-versa, after which it was returned back to the respective BTF.

The following operating parameters were considered for carrying out the experiments: gas flowrate = 0.75 L/min; initial ethanol concentration = 100 to 550 ppm, depending on the undertaken trial; ambient CO₂ concentration (350-450 ppm); nutrient solution flowrate = 0.2 L/min; nutrient solution volume = 2.5 L; ambient temperature (22-26 °C).

The performance of BTFs was evaluated in terms of typical criteria such as [2, 3, 12]: elimination capacity (EC, mass / (packing bed volume • time), loading rate (LR, mass / (packing bed volume • time), carbon dioxide production rate (P<sub>CO₂</sub>, mass / (packing bed volume • time)) and removal efficiency (%).

3. Results and discussions

3.1. Co-immobilisation impact on CO₂ production and global warming potential

The impact of the microalgae co-immobilisation with microorganisms derived from compost is exemplified in Figure 2, where it can be seen that operating the BTFs in co-immobilised version (BTF1 and BTF2) is associated with a lower CO₂ production than in the case of a classical BTF (sole compost-based microorganisms e.g. prior co-immobilisation), under the same experimental conditions (e.g. LR = 462 ± 16 g/(m<sup>3</sup> • d)). Thus a significant decrease in global warming potential (GWP), which is closely related to P<sub>CO₂</sub> decrease, is obtained. Particularly, the highest P<sub>CO₂</sub> reduction is recorded for BTF2 (Figure 2). As can be seen in Figure 3, both bacteria and microalgae were present in BTF1 and BTF2, with a higher microalgae:bacteria ratio in BTF2. This can explain the better BTF2 performance in terms of P<sub>CO₂</sub> reduction, taking into consideration the role of microalgae in CO₂ uptake through photosynthesis process. Other observed biota include some yeasts, fungi, but also protozoa, which have been also reported in other studies involving compost-based microorganisms for ethanol biotrickling filtration[13]. It is interesting to note that protozoa presence could be associated with a self-cleaning effect of excess accumulated biomass (a complementary benefit), which in turn could result in a higher CO₂ production[14-16]. This last mentioned drawback could be overcome by an adequate symbiosis between microalgae (CO₂ consumers) – bacteria - protozoa.
Figure 2. Carbon dioxide production rate ($P_{CO_2}$) for different BTF configurations, at LR = 462 ± 16 g/(m$^3$·d). BTF-compost = classical BTF version, involving sole compost-derived microorganisms; BTF1, BTF2 = upgraded BTF versions, involving co-immobilised microalgae and compost-derived microorganisms in different ratios; GWP = global warming potential.
Figure 3. Microscopic investigation of the involved microorganisms.

3.2. Loading rate, elimination capacity and CO\textsubscript{2} production

As expected, P\textsubscript{CO2} still increases with the increase of ethanol concentration (or loading rate) [13], however this increase is smaller for BTF2 than for BTF1, while a maximum ethanol removal efficiency is obtained for all runs (Figure 4). A temporary increase in ethanol concentration in the treated gas was observed in the middle of the interval, but this was due to nitrogen consumption in the nutrient solution. After nitrogen supply, the removal efficiency recovered back. A pH stabilisation trend around 9.2 was observed as result of co-immobilisation, despite the ethanol input, which suggests the beneficial role of the involved microorganisms symbiosis in the system.

The correlation between EC and P\textsubscript{CO2} is shown in the following figure, where the reference linear curve is related to the oxidation of the ethanol without any biomass production [3]. The slopes obtained for BTF1 and BTF2 indicate that 53-68\% of ethanol is recovered as CO\textsubscript{2} in the treated gas, which is smaller than those observed in other studies with classical bioreactors where often around 80\% is typically reported (the remaining part being used for the biomass development in the BTF) [3, 17]. This aspect, as well the very small values for the intercepts, confirms the CO\textsubscript{2} consumption by the microalgae in the actual study.
Figure 4. Variation of carbon dioxide and ethanol concentration as a function of time in BTFs with the co-immobilised microorganisms

Figure 5. Carbon dioxide production rate ($P_{CO2}$) as a function of the ethanol elimination capacity (EC)

4. Conclusions
This study shows that co-immobilisation of microalgae with specific compost-based microorganisms can significantly contribute to the environmental performance of the BTF treating VOCs in air, by increasing the overall C-capture and decreasing the global warming potential. The involved microorganisms are able to act symbiotically, forming a specific biological system where each type of microorganism has each own function contributing to the overall process performance. For instance, maximum ethanol removal is obtained for all tested initial concentrations, while achieving a smaller CO2 production.

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