INFLUENCE OF KEY PARAMETERS ON THE REMOVAL EFFICIENCY OF AIR POLLUTANTS BY A BIOTRICKLING FILTER

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ABSTRACT
A chemical scrubber followed by a biotrickling filter (BTF) was integrated in the air treatment line of a composting plant, originally equipped with an open-bed biofilter. Such integration is motivated by the poor performance of the biofilter in the removal of odorants like ammonia (NH_3), sulphides and volatile organic compounds (VOCs). The scrubber and BTF units were monitored during two summer periods in two consecutive years (08.10.2016–09.13.2016 and 07.26.2017–09.20.2017) by analysing key parameters such as airflow rate, metabolite concentrations and, especially, the temperature of the circulation water of the BTF. During the second period, a 17% decrease in the waste-gas flow rate and a consequent increase in the waste-gas temperature were measured. The control of temperature proved to be crucial for the removal of the three groups of pollutants investigated in this study. The occurrence of thermophilic conditions in the BTF inhibited nitrification and generally lowered VOC biodegradation. The increased NH_3 removal rate that was observed during the second period can only be explained with the increase in the residence time in the scrubber, as an analysis of the nitrate and ammonium concentrations in the circulation water of the BTF revealed. While adverse temperature conditions may be compensated by increased residence time for NH_3, temperature is crucial for VOCs, which were only slightly affected by the increased residence time. On the other hand, a relative increasing trend of VOC removal rate in the BTF was observed in the thermophilic range. In addition, the removal efficiency of dimethyl sulphide clearly increased during the second period. More research is needed to understand if such a positive effect can be related to the increased residence time in the pre-treatment line or if thermophilic conditions can help the biodegradation of VOCs and sulphides.
Keywords: biofiltration, air pollution control, absorption, volatile organic compounds, dimethyl sulphide, ammonia.

1 INTRODUCTION

In spite of the evident advances in the emission control from industrial and civil activities, air pollution is still an alarming issue related to the continuous economic growth of developed and developing countries around the world, which determines an increasing number of activities that release air pollutants into the atmosphere [1]. Ozone, particulate matter (PM) and ammonia (NH_3) act on a regional scale, the first two being transported over hundreds of kilometres and the last one promoting secondary PM formation [2]–[4]. Ozone also induce global warming on a global scale [5] PM also acts on a local scale, inducing respiratory and cardiovascular diseases [6], as well as nitrogen dioxide, carbon monoxide, volatile organic compounds (VOCs) and micropollutants. VOCs may be directly harmful to humans through inhalation and may promote ozone formation [7]. In addition, NH_3 and other nitrogen-based compounds, several VOCs and sulphur-based compounds may be perceived by the sense of smell at low concentrations, thus inducing odour nuisance to people living near activities that emit such substances [8].

Physical and chemical methods (e.g., thermal or catalytic oxidation, absorption, catalytic reduction and adsorption) have been largely and conveniently used to remove gaseous air pollutants when the polluted airflow is characterised by high pollutant concentrations

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(> 100 ppm) and low-to-medium flow rates (< 10^4 Nm^3/h) [9], [10]. The treatment of large airflow rates characterised by lower pollutant concentrations have proved to be more conveniently achieved by methods that limit the use of fuels, electric energy and chemicals [11]. This is the case, for instance, of biofiltration, which is a widespread, simple and cost-effective technology that is especially convenient to remove a large variety of air pollutants at low concentrations (generally < 100 ppm) but with medium-high airflow rates (> 10^4 Nm^3/h) [12]. Such operating conditions are typical of mechanical-biological treatments (MBTs) of municipal solid waste like composting. In fact, biofiltration has become a fundamental component of the air pollution control lines of MBTs.

Composting and other aerobic MBTs (e.g., biostabilisation and biodrying) emit a large variety of compounds compared to specific industrial activities. The major constituents of the process air of aerobic MBTs include volatile organic compounds (VOCs), nitrogen- and sulphur-based compounds. Among VOCs, the main groups of compounds in the process air are aromatics, ketones, aldehydes, terpenes, volatile fatty acids and alcohols [13]. Nitrogen- and sulphur-based compounds are mainly ammonia (NH_3), ammines, hydrogen sulphide, dimethyl sulphide (DMS) and dimethyl disulphide [14], [15]. All VOCs except aromatics are generated by incomplete aerobic biodegradation, while sulphides are formed by local conditions of anaerobic biodegradation that can develop in the waste piles the porosity of waste is low [13], [16]. Ammonia and ammines are formed as degradation products of proteins [16]. Aromatic VOCs and other micropollutants (e.g., dioxin) may be released by MBT facilities too. Contrarily to the previous compounds, such substances are not formed during the biodegradation process but are already present in the waste. The presence of aromatics may be due to the disposal of solvents in the waste, while the presence of dioxin may be related to the presence of contaminated food waste [17]. Indeed, it is known that about 90% of the human daily exposure to dioxin occurs through the diet [18].

Traditionally, biofiltration is carried out by open-bed biofilters, which requires large areas to ensure satisfying residence time and homogeneous conditions along the vertical direction. More recently, as an alternative to traditional biofilters, biotrickling filters (BTFs) have gained consideration because of their more compact size, lower pressure drop, effective pH control and due to the possibility of removing different pollutants that require different pH conditions and bacterial strains [19]. Indeed, contrarily to biofilters, BTFs can be easily divided into two or more stages operating under different pH conditions and inoculated with the most suitable microorganisms for the removal of the pollutants.

The control of temperature in a BTF is particularly important because temperature influences the reproduction of the microorganisms that carry out the biodegradation process. Mesophilic conditions, with temperatures in the range 10–40°C, are the most suitable for most of the bacterial strains and, consequently, for most of the pollutants that are removed by biofiltration [20]. Generally, temperatures in the thermophilic range (> 45°C) may cause the death of most of the microogranisms. This should be taken into account even when operating a BTF under mesophilic conditions, since biodegradation is an exothermic process [19]. Nevertheless, thermophilic conditions are favourable in specific situations, e.g. when the target is to remove nitrogen oxides from an airflow [21]–[23]. On the other hand, temperatures in the cryophilic range (< 20°C) may inhibit the microbial activity [24].

The present paper describes the operation of an air treatment system used to pre-treat the air extracted from the biocells of a composting plant treating the organic fraction of municipal solid waste (OFMSW). The latter is located in northern Italy and was object of numerous complaints by the local population, due to the odour nuisance perceived in the area, which was related to a malfunctioning of the existing open-bed biofilter, caused by the high concentrations of NH_3 in the waste-gas flow and by the high waste-gas temperature. In addition, high concentrations of VOCs and sulphides were detected in the waste gas, which were generated by anaerobic zones in the biocells. Sulphides like DMS are characterised by lower odour threshold levels compared to other compounds that are generally formed during composting [7]. To reduce the concentrations of odorants in the waste gas upstream of the existing biofilter, a pre-treatment line was installed. The latter is composed of a chemical scrubber and a BTF. In the attempt to decrease the waste-gas temperature, the gas flow rate to the pre-treatment line was increased by drawing the air of the compartment assigned to receive the incoming waste.

In view of the history of the composting plant, the aim of this paper is two-fold:

- to evaluate the technical convenience of pre-treating the heavily polluted air coming from the biocells of a composting plant through advanced biological systems, alone or in combinations with chemical scrubbers;
- to investigate the impact of different process parameters (including the waste-gas temperature) on the performance of the pre-treatment stage, especially on the capability of removing NH_3, VOCs and DMS.

2 MATERIALS AND METHODS

2.1 Description of the air pre-treatment line

The waste gas coming from the biocells for the accelerated oxidation of OFMSW (about 8,550 m^3/h at about 65°C) is mixed with the waste gas coming from the reception compartment (28,575 m^3/h at about 30°C) in the attempt to reduce the gas temperature. The waste gas is then sent to the chemical scrubber operated with a washing solution (1,400 L/min) based on sulphuric acid (H_2SO_4) to abate NH_3. The scrubber consists in a column composed of two chambers filled with spheres of polyethylene.

The waste gas is then sent to a BTF, designed to operate at a temperature of 40°C, for the removal of peaks of NH_3, VOCs and sulphides. The filling material consists in shells, which ensures pH stability in case of production of acidic by-products during biodegradation. In addition, the BTF, in an appropriate range of temperature between 25 and 35°C [25], is capable of operating the nitrification of the residual NH_3 coming from the chemical scrubber. The BTF ensures a residence time of 16 s at the total airflow rate (37,125 m^3/h at 38°C). The washing solution is recirculated over the filling material with a flow rate of 160 L/min.

The biofilter, originally treating a waste-gas flow rate of 84,000 m^3/h coming from the biocells and the maturation stage, is now requested to treat the additional 28,575 m^3/h from the reception compartment. Consequently, the specific volumetric load increased from 44 to 60 m^3/h per m^3 of filling material.

2.2 Air sampling

The efficiency of the air treatment stage of the composting facility was monitored through the analysis of air samples collected by seven sampling points along the air treatment line. Specifically, three air sampling ports are located at the inlet of the chemical scrubber (A), at the inlet of the BTF (B), at the outlet of the BTF and downstream of the blower (C). Fig. 1 presents a schematic view of the layout of the air treatment stage of the composting facility and of the locations of the three sampling points.

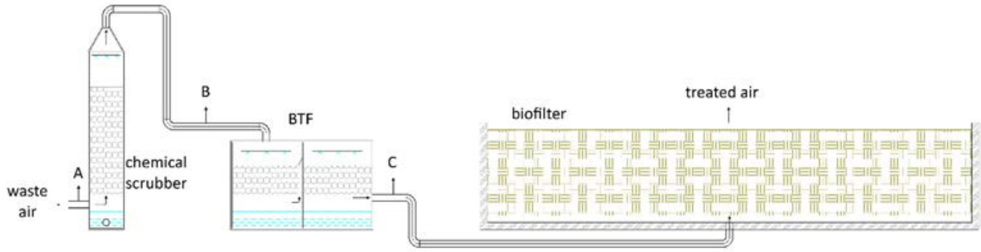

Figure 1: Layout of the air treatment line of the composting facility.

2.3 Analytical methods

The concentrations of NH_3 and DMS in the process air were measured by means of colorimetric vials (Drägerwerk AG & Co. KGaA, Germany), inserted into the sampling ports A, B and C, allowing for measuring NH_3 in the ranges 2–30 ppm and 5–100 ppm, and DMS in the range 0–15 ppm. The total VOC concentration in the process air was monitored by a photoionisation detector (MiniRAE Lite, RAE Systems, USA), allowing for measuring VOC concentrations in the range 0–5,000 ppm in the sampling points A, B and C. A hot-wire anemometer (HD 2303.0, Delta OHM Srl, Italy) was used to measure the temperature and the flow rate of the process air in the sampling point A. In addition, the temperature and the concentration of ammonium (NH_4^+) and nitrates (NO_3^{2-}) ions were monitored in the circulation water of the BTF. Finally, the pH of the washing solution of the scrubber and the pressure drop between the BTF were respectively monitored by a pH-meter and digital differential manometers. Two measurement campaigns were carried out in two consecutive years: the first one took place in the period 08.10.2016–09.13.2016 and the second one was performed in the period 07.26.2017–09.20.2017.

3 RESULTS AND DISCUSSION

3.1 NH_3 removal

The removal of NH_3 from the process air of the composting facility is preliminarily carried out by the scrubber through chemical absorption. Generally, the absorption of NH_3 increases both with the contact time of the pollutant with the washing solution and with decreasing the pH of the washing solution.

The effect of the contact time is visible by comparing the removal efficiency of NH_3 between the two study periods, since the flow rate of the process air was decreased by 17% between 2016 and 2017 by the company that manages the composting plant (Fig. 2). During the whole observation period, the pH remained almost constant and comprised between 4.0 and 4.7. The NH_3 concentration at the inlet of the scrubber varied between 6 and 60 ppm during the two monitoring periods. Overall, the chemical scrubber allowed obtaining NH_3 removal efficiencies > 85%, determining an NH_3 concentration at the inlet of the BTF < 2.5 ppm (mean value: 0.6 ppm).

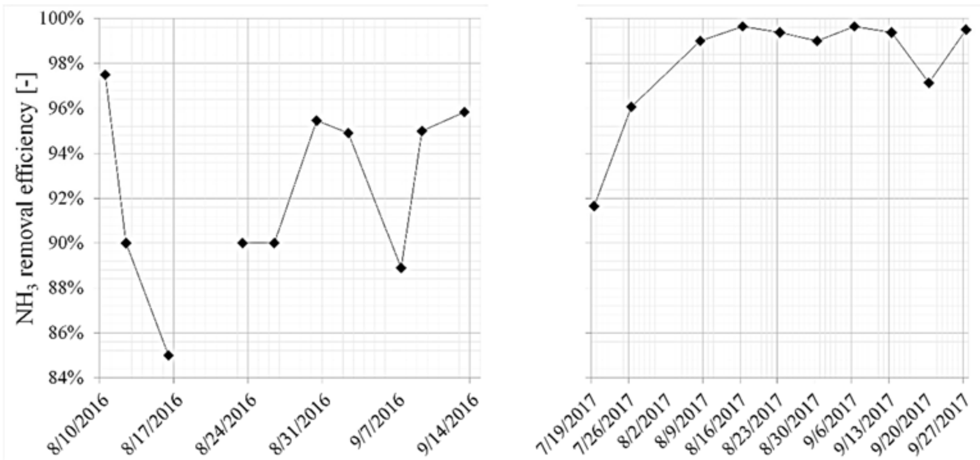

Figure 2: Trends of the removal efficiencies of NH_3 by the chemical scrubber during the first and the second monitoring period.

The removal performance of NH_3 by the BTF was not as constant as that of the chemical scrubber for the same observation period. These results are confirmed by the trend of the concentrations of NH_4^+ and NO_3^{2-} in the circulation water of the BTF. Specifically, NO_3^{2-} concentration in the circulation water is a good indicator of the biological activity of the microorganisms present in the BTF, since a well-performing biological oxidation process transforms NH_4^+ into NO_3^{2-} through nitrification. Therefore, by assuming the airflow rate, the circulation water and nutrient flow rates and the inlet NH_3 concentration as constant, a decrease in the NO_3^{2-} concentration in the circulation water over time would indicate that the biological activity of the microorganisms is weakening. This would be accompanied by an increase in the NH_4^+ concentration in the circulation water. The concentration trends of NH_4^+ and NO_3^{2-} in the circulation water are reported in Fig. 3.

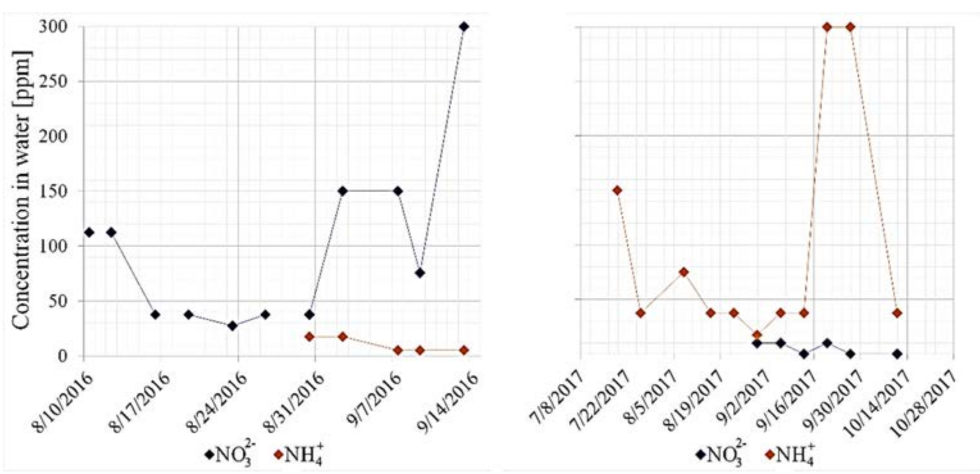

Figure 3: Trends of the concentrations of NO_3^{2-} and NH_4^+ in the circulation water of the BTF during the first and the second monitoring periods.

The concentration trends of NH_4^+ and NO_3^{2-} are not constant over time. This behaviour could be partly related to the high temperature of the circulation water, which reaches peaks > 45°C, especially during summer 2017. Nitrification is known to take place under mesophilic conditions [25]. Under thermophilic conditions, nitrification is inhibited. This may explain the low concentrations of NO_3^{2-} in the circulation water. The high temperature of the washing solution of the BTF experienced in September 2017 explains the significant increase in the NH_4^+ concentration. This event is associated with an increase in the NH_3 concentration at the outlet of the BTF.

3.2 DMS removal

An increase in the overall removal efficiency of DMS was observed during the second monitoring period (summer 2017) with respect to the first one (Fig. 4). This increase may be due to the increase in the residence time caused by the decrease of the airflow rate that occurred in the second year. An additional explanation could be related to the increase in the temperature of the circulation water of the BTF that might have created favourable conditions in the BTF. However, this hypothesis is not supported by the scarce number of scientific papers in the literature [27]. To prove this hypothesis, the concentration of DMS should be measured in B. However, such measurements are not available at present.

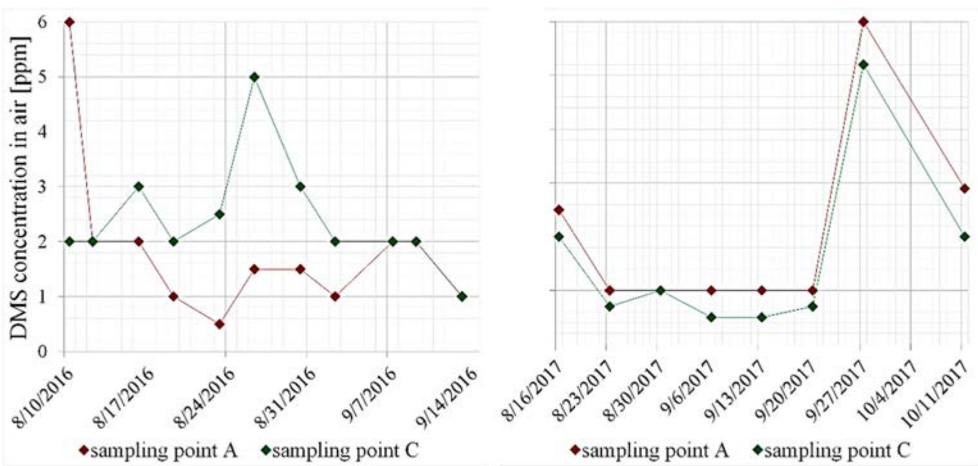

Figure 4: Trends of the DMS concentrations measured in the sampling points A and C during the first and the second monitoring periods.

3.3 Total VOC removal

During the two monitoring periods, the VOC concentrations at the inlet of the scrubber varied between 5.9 and 51.2 ppm (Fig. 5). A decrease in the VOC removal efficiency of the scrubber-BTF combined system can be observed in 2017 compared to the previous year. Such lower performance may be due to the transition to thermophilic conditions in the BTF, which may have slowed down the activity of the microorganisms performing VOC biodegradation. The very low removal efficiencies in the scrubber indicate that most of the removal process occurs in the BTF. In fact, absorption is known not to represent an efficient option for VOC removal, due to the generally low solubility of VOCs in water [26].

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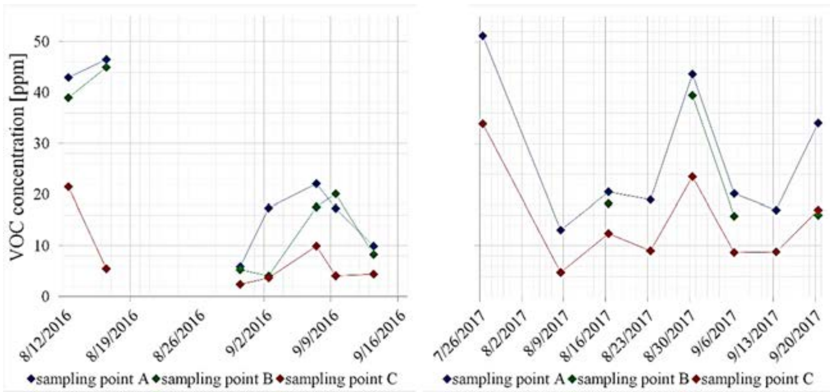

Figure 5: Trends of VOC concentrations during the first and the second monitoring periods.

3.4 Effect of temperature

In the attempt of understanding how the temperature can influence the removal of the three investigated categories of pollutants, Fig. 6 reports the relationships between the removal efficiencies of NH_3, DMS and VOCs as a function of the temperature of the circulation water in the BTF, by assuming a temperature of 40°C as a threshold value for the transition between mesophilic and thermophilic conditions.

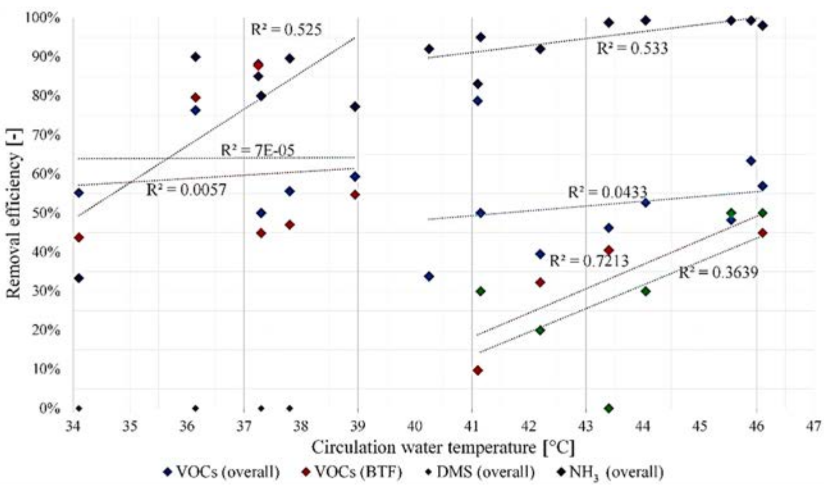

Figure 6: Relationships between the circulation water temperature in the BTF and the removal efficiencies of NH_3, DMS and VOCs; overall removal efficiencies refer to the abatement by the scrubber-BTF system.

Concerning VOCs, the available data allow calculating both the removal efficiencies of the scrubber-BTF system and the removal efficiencies of the BTF alone. Regarding DMS, due to the lack of data in B, only the removal efficiencies of DMS by the scrubber-BTF system were included in Fig. 4. Similarly, the relationship between temperature and NH_3 removal efficiency is presented only with respect to the scrubber-BTF system. A decreasing trend in the removal efficiencies of total VOCs is visible at increasing temperature in the circulation water of the BTF. The highest temperature generally occurs during 2017, when the waste-gas flow rate was 17% lower than 2016 on average. This confirms that, in spite of an increase in the residence time, an increase in temperature negatively affects total VOC removal. Concerning the only BTF, the VOC removal efficiency seems to increase after transition to thermophilic conditions. However, the removal efficiencies obtained under such circumstances are lower than those achieved in the mesophilic range of temperature. Additional tests should be carried out at higher temperatures to confirm the positive effect of temperature. Regarding NH_3, the increase in the overall removal efficiency with temperature is only apparent, since nitrification is inhibited under thermophilic conditions. Therefore, the overall improvements in the NH_3 removal efficiency may be related to the increase in the contact time in the chemical scrubber, due to the decrease in the airflow rate that occurred in 2017, the same period during which the temperature of the circulation water increased. The abatement performance of DMS seems to increase at increasing the temperature of the washing solution of the BTF.

This behaviour can be explained both by the increased residence time in 2017 (when higher temperatures were measured) and by a possible favourable situation to sulphide-degrading microorganisms determined by thermophilic conditions. To confirm this effect, measurements of the DMS concentration in B are needed. If this effect were confirmed, thermophilic conditions could facilitate the removal of sulphides.

If the main target is to reduce NH_3 and VOC concentrations upstream of a biofilter, two alternative options are available:

- the company that manages the composting plant could insert a heat exchanger upstream of the pre-treatment line to cool down the waste-gas flow rate, if its temperature is incompatible with the optimal conditions for nitrification in a BTF;
- the waste-gas flow rate could be further increased by an amount of colder air coming from outside or from internal compartments with low pollutant concentrations (e.g., the reception compartment or the last maturation stages).

Both the options must be evaluated by the company managing the plant, since additional costs would be involved: the first option would imply the condensation of part of the waste gas, which would require additional operational costs to treat the generated wastewater; the second option would entail the enlargement of the treatment line (e.g., an additional stage in the BTF), with additional investment costs.

4 CONCLUSIONS

The air pollution treatment line of a composting facility was monitored during two observation periods. The line comprises a chemical scrubber and a BTF upstream of a biofilter. Special attention was given to assess the performance of the first two elements of the treatment line, which, if properly operated, would ensure lower pollutant loads to the biofilter and, consequently, higher overall removal rates. In view of improved performance, the control of the temperature of the system proved to be crucial. Specifically, the establishment of thermophilic conditions showed adverse effects on the biodegradation of NH_3 in the BTF and a reduced performance in the overall VOC abatement. A decrease in the airflow rate occurred during the second period of observation and this may explain the increase in the removal rate of NH_3, thanks to a consequent increase in the residence time. However, the temperature of the circulation water increased at the same time and this could be considered as a positive factor towards the removal of DMS that was observed in the thermophilic range. Additional confirmations of the effects of high temperature on DMS removal would be available if the concentrations of DMS were measured upstream of the BTF (sampling point B). If the positive effect of temperature were confirmed, the increase in the DMS removal during the second monitoring period could be related to the occurrence of thermophilic conditions and this could open to additional options in the field of air pollution control. The increase in the residence time did not have positive effects on VOC removal and this behaviour may be explained with the low solubility of VOCs in water. While adverse temperature conditions may be compensated by increased residence time for NH_3, temperature is a crucial factor for VOC removal. The complete monitoring of key parameters (pollutant concentrations in air and in water, metabolite concentrations, temperature, pH and airflow rate) in all the sampling points located upstream and downstream of each component would allow for the correct management of a multi-step air pollution treatment line and would give definitive indications on their role.

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