

1 **Performance and Feasibility of Biotrickling Filtration in**
2 **the Control of Styrene Industrial Air Emissions**

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23 **Abstract**

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25 The performance and feasibility of a pilot unit of biotrickling filter (BTF) for the treatment of
26 industrial emissions polluted by styrene was investigated for one year at a fiber reinforced
27 plastic industrial site. The pilot unit was packed with a structured material with a volume of
28 0.6 m^3 . Monitoring results have shown successful treatment of the industrial styrene
29 emissions working at empty bed residence times (EBRT) between 31 and 66 s. The best
30 performance was obtained after 300 days when a more stable biofilm had been developed,
31 obtaining the highest elimination capacity of $18.8 \text{ g m}^{-3} \text{ h}^{-1}$ (removal efficiency of 75.6%)
32 working at 31 s of EBRT. In addition, a photocatalytic reactor was evaluated as pretreatment
33 of the biological process, but results have shown very low capacity for improving the BTF
34 performance due to catalyst deactivation. The economic feasibility of the BTF was evaluated.
35 The total direct cost, excluding capital recovery, of the biotrickling filter technology was
36 estimated in 0.71 € year^{-1} per $\text{Nm}^3 \text{ h}^{-1}$ of treated air whereas 2.27 € year^{-1} per $\text{Nm}^3 \text{ h}^{-1}$ was
37 obtained for the regenerative catalytic oxidizer equipped with a zeolite pre-concentrator.
38 Results show that this technology is economically and environmentally competitive in
39 comparison with thermal treatment.

40

41 **Keywords:** air emission, biotrickling filter, economic feasibility, pilot unit, fiber reinforced
42 plastic industry, styrene

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45 **1. Introduction**

46 Styrene (C₈H₈) is a volatile organic compound (VOC) and among its chemical and
47 physical characteristics can be highlighted a vapor pressure of 0.667 kPa at 20 °C, a water
48 solubility of 300 mg L⁻¹ at 20°C and a log value of the octanol-water partition coefficient of
49 3.02. Styrene has been classified as dangerous substance with risk-phrases H226 (Flammable
50 liquid), H315 (Skin irritation), H319 (Eye irritation), H332 (Harmful if inhaled), H361d
51 (Suspected of damaging the unborn child) and H372 (Causes damage to organs through
52 prolonged or repeated exposure) (European Commission, 2002). Kuhn et al. (2000) evaluated
53 the ecotoxicity of styrene and it was identified as toxic to aquatic organisms, flora, fauna, soil
54 organisms, bees and hazardous to water. Derwent et al. (1998) estimated a styrene
55 photochemical ozone creation potential of 14.2. Styrene is extensively used as an intermediate
56 in the chemical industry. One of the main applications is as a component of polyester resins in
57 the fiber reinforced plastics industry that yearly produces over one million tons of composites
58 in Europe (Witten et al., 2015). In this sector, styrene evaporates from exposed uncured resin
59 surfaces into the atmosphere during processing until the resin is fully cured (Di Tomasso et
60 al., 2014) resulting in waste gases characterized by high flow rates and low pollutant
61 concentrations. Nowadays, air emission regulations require techniques to treat these emissions
62 because of the adverse effects of styrene on human health (Miller et al., 1994) and its
63 classification as hazardous air pollutant (USEPA, 1994). In the control of styrene air
64 emissions, both the regenerative thermal oxidizer (RTO) and the regenerative catalytic
65 oxidizer (RCO) are the established technologies, although biological processes can be seen as
66 potential alternative to these chemical methods due to their low operational costs and lack of
67 secondary pollutant generation (Zhang et al., 2016).

68 In recent decades, styrene removal by biofiltration has been studied at laboratory by
69 using biofilters and biotrickling filters (Arnold et al., 1997; Dehghanzadeh et al., 2005; Novak

70 et al., 2008; Sempere et al., 2011). Biotrickling filter (BTF), with an aqueous stream trickling
71 through an inert packing material, provides advantages in comparison with conventional
72 biofilter (BF) such as higher removal rates, lower energy consumption and smaller footprint
73 requirements (Pérez et al., 2015). In this sense, Halecky et al. (2016) compared the
74 performance of a BTF packed with Pall rings and a BF packed with Poraver media during the
75 treatment of vapors polluted with a 2:1 (wt:wt) mixture of styrene and acetone. BTF showed
76 higher removal efficiencies (REs) with a maximum styrene elimination capacity (EC) of 13 g
77 $\text{m}^{-3} \text{h}^{-1}$ in comparison with 8.7 $\text{g m}^{-3} \text{h}^{-1}$ of EC for the BF. Pérez et al. (2015) obtained similar
78 values of EC $\sim 55 \text{ g m}^{-3} \text{h}^{-1}$ for an inlet load (IL) $\sim 85 \text{ g m}^{-3} \text{h}^{-1}$ in a peat BF and a BTF packed
79 with polypropylene rings, both working at an empty bed residence time (EBRT) of 45 s.
80 However in terms of energy consumption, the BTF presented values of pressure drop ($< 59 \text{ Pa}$
81 m^{-1}) substantially lower than the peat BF (around 500 Pa m^{-1}).

82 Pilot studies of styrene removal are still scarce thus making difficult its industrial
83 implementation. Lackey et al. (1998) evaluated a 1.23 m^3 BF packed with a mixture of pine
84 bark and composted chicken litter treating emissions polluted with styrene, methyl ethyl
85 ketone and acetone from a boat manufacturing facility. The pilot BF was tested during 13
86 months under inlet styrene concentrations varying from 0 to 380 ppm. Styrene REs greater
87 than 99% were obtained when EBRTs higher than 150 s were applied. Webster et al. (1999)
88 tested a 8 m^3 BTF packed with plastic spheres to control styrene emissions from a fiberglass
89 bathtub manufacturing facility. A maximum EC of $24 \text{ g m}^{-3} \text{h}^{-1}$ (RE 70 – 85%) was reported
90 at inlet concentrations up to 800 mg m^{-3} for EBRT of 86 s. Further research with pilot plant
91 studies in industrial sites are needed for demonstrating the robustness of the technology,
92 providing practical information of the performance of the process under fluctuating and
93 oscillating emissions.

94 An alternative to improve the VOC removal in biological processes can be the use of
95 photo-oxidation/photocatalytic pretreatment, which could be able to convert the VOC
96 compounds in more easily biodegradable by-products with the aim of enhancing the
97 biodegradation. Recent examples of studies combining UV photodegradation with
98 biofiltration are shown in Table 1. As it can be seen, studies have been mainly focused on
99 toluene, o-xylene and chlorinated compounds, but studies on styrene are very scarce. For
100 example, Runye et al. (2015) studied a UV photo-oxidation reactor combined with a BTF in
101 the removal of air contaminated with styrene and observed a maximum EC of $309 \text{ g m}^{-3} \text{ h}^{-1}$ at
102 an IL of $476 \text{ g m}^{-3} \text{ h}^{-1}$ working at EBRTs of 10 and 30 s in the photodegradation reactor and in
103 the BTF, respectively. Studies of integrating UV photocatalysis and BTF or BF treatments in
104 the removal of styrene have not been found.

105 The scope of this work was to assess feasibility of a pilot-scale biotrickling filter in the
106 control of styrene air emissions emitted from a facility that manufactures fiber reinforced
107 composite profiles and tubes. The following objectives were taken into account: (1) to
108 demonstrate the effectiveness and robustness of the technology under fluctuating and
109 oscillating industrial emissions, (2) to evaluate the influence of the empty bed residence time
110 in the removal efficiency, (3) to carry out an economic feasibility study of the application of
111 the BTF technology in this industrial sector, and (4) to analyze the effect on the BTF
112 performance of using an UV photocatalytic reactor as pretreatment.

113

114 **2. Materials and Methods**

115 2.1 Pilot-scale system

116 The pilot-scale BTF plant which was provided by Pure Air Solutions B.V. (The
117 Netherlands) is based on the VOCUS® Biotrickling filter system. This bioreactor design has
118 been widely used to successfully treat VOCs or VICs in waste gases at field-scale in other

119 industrial sectors such are wastewater treatment plants, flexographic, automotive and wood
120 coating (Álvarez-Hornos et al., 2011; Lafita et al., 2012a, 2012b; Sempere et al., 2012). The
121 pilot plant was installed inside the factory. Figure 1 presents the scheme of the pilot BTF. The
122 biological reactor, a column with an effective volume of 0.6 m³, was packed with a structured
123 packing material (PAS Winded Media) with a 93% void fraction and 410 m² m⁻³ of specific
124 surface area. A recirculation tank of 0.4 m³ of volume was installed to collect the trickling
125 water and was equipped with a level control and fresh water was added when it was
126 necessary. A fraction of the waste gases from the factory without dilution was fed to the pilot
127 unit by using a blower equipped with a variable-frequency drive. The polluted air was
128 introduced below the column at a flow rate varying from 33 to 71 Nm³ h⁻¹ and the recirculated
129 water was intermittently sprayed on the top of the filter media (counter-current mode) at a
130 flow rate of 2.7 m³ h⁻¹ (spraying frequency: 10 min per h). The nutrient dosing system was
131 composed of a 100 L vessel and a dosing pump. The nutrient solution (70 g L⁻¹ of Urea, 34 g
132 L⁻¹ of (NH₄)₂HPO₄, traces of Mg, Ca, Fe, Zn, Co, Ni, Mn, Mo, B, yeast and vitamins) was
133 pumped to the recirculation tank to achieve a C_{loaded}/N_{supplied} mass ratio above 30 – 40, thus
134 assuring that nitrogen concentration in the trickling solution did not limit the biodegradation.
135 Occasionally, when the pH of the trickling solution dropped below 6.7, a control procedure
136 was carried out adding manually 40 g of NaHCO₃ to the recirculation tank. Around 50% of
137 the volume of the recirculation tank was partially drained and replaced with fresh water once
138 a month. The pilot unit was equipped with sensors and devices (temperature, pressure, etc.)
139 connected to a programmable logic controller.

140 The design of the photocatalytic pilot unit was based on our previous laboratory
141 experiment treating toluene, m-xylene and n-butyl acetate at two residence times: 6 and 12 s
142 (Palau et al., 2011). An intermediate value of 10 s was chosen for the industrial testing. The
143 photocatalytic pilot unit consisted of a steel box (0.5 m high, 0.5 m wide and 0.75 m long),

144 with a volume of 0.19 m³. The polluted air flowed through 6 panels with glass fiber
145 impregnated with TiO₂ catalyst and 5 stands with 5 UV lights alternative placed. A total of 25
146 commercial UV lamps (Philips® Tuv-25W, The Netherlands) with an external diameter of 28
147 mm and a lifetime of 9000 h were placed on the 5 stands at 0.5 cm and 7.5 cm from the panels
148 with the catalyst. The TiO₂-glass wool supported catalyst was prepared using the wash-coat
149 method. The glass wool support was impregnated with a suspension of 5% wt of TiO₂
150 (Aeroxide P-25 from Degussa, Germany) in water. It was then dried for 1 h at 120 °C and
151 calcined for 3 h at 350 °C. The UV lamp has a spectral output centered at a wavelength of 254
152 nm. The light intensity was 355 μW/m² and 180 μW/m² at 0.5 and at 7.5 cm, respectively
153 (Minolta, UV radiometer UM-10 equipped with a sensor UM-250, Japan). There was no
154 observed significant decrease in light intensity thorough the study.

155 The BTF pilot unit was running for one year in two consecutive stages. In stage I, the
156 BTF was started up and operated for 4 months at three different EBRTs: 66, 42 and 31 s with
157 the aim of evaluating the influence of the residence time on the removal efficiency. In stage
158 II, the BTF pilot unit was working during 8 months under a constant EBRT of 31 s in order to
159 study the stability and the robustness of the technology. At the end of this phase, in order to
160 evaluate the effect of the photocatalytic reactor as pretreatment, this one was installed prior to
161 the BTF unit. The styrene emissions were firstly treated in the photocatalytic reactor
162 (residence time of ~10 s) and then were fed to the BTF at an EBRT of 31 s. The BTF was
163 inoculated with activated sludge from the secondary clarifier of the Zuiveringsgebied-
164 Oudenaarde Wastewater Treatment Plant (Oudenaarde, Belgium) without further acclimation.
165 An inoculum volume of 200 L was added to the recirculation tank and flowed during 24 h
166 through the bed with a fixed spraying frequency of 30 min per h.

167 The EBRT (s), RE (%), IL (g m⁻³ h⁻¹) and EC (g m⁻³ h⁻¹) were determined using the
168 equations defined below linking the inlet styrene concentration, C_{in} (g Nm⁻³), the outlet

169 styrene concentration, C_{out} (g Nm^{-3}), the gas flow rate, Q ($\text{Nm}^3 \text{h}^{-1}$), and the effective reactor
170 volume, V (m^3):

171

$$172 \quad EBRT = V/Q \cdot 3600 \quad (1)$$

173

$$174 \quad RE = 100 \cdot (1 - C_{out}/C_{in}) \quad (2)$$

175

$$176 \quad IL = C_{in} \cdot Q/V \quad (3)$$

177

$$178 \quad EC = (C_{in} - C_{out}) \cdot Q/V \quad (4)$$

179

180 2.2 Analytical methods

181 Inlet and outlet gas temperatures, air flow rate, the bed pressure drop, tank levels, and
182 the conductivity, pH and temperature of the trickling solution were continuously monitored.
183 Inlet and outlet total VOC concentrations were daily measured by using two photo ionization
184 detectors (PID) equipped with 10.6 eV lamps (TVOC, Ion Science Ltd., UK). The PID
185 sensors were checked and calibrated by using a total hydrocarbon analyzer equipped with a
186 flame ionization detector (Nira Mercury model 901, Spirax-Sarco, Spain) which was
187 calibrated using a synthetic standard mixture of propane (1000 ppm) in nitrogen gas
188 (Carbueros Metálicos, Spain). Samples of the recirculated water were collected (twice per
189 month) to analyze chemical oxygen demand (COD), nitrogen and phosphorus content. The
190 identification and quantification of the main compounds presented in the waste gas emissions
191 were carried out by collecting samples by using a GiLAir Pump (model GA-5) and activated
192 carbon tubes (type 226-09: 400–200 mg, SKC, UK) subsequently analyzed by gas
193 chromatography.

194

195 **3. Results and Discussions**

196 3.1 Characterization of emissions from the facility

197 The industrial site manufactures fiber reinforced composite profiles and tubes for
198 demanding industrial applications by pultrusion. The factory operates with continuous 8-h
199 work-shifts, 24 h per day, from Monday 6:00 am with shut down periods on weekends.
200 Regarding the waste gas stream, the daily average temperature of the emission varied between
201 16 and 30 °C, with an average of 21.5 ± 4.5 °C, for the whole test period due to changes in the
202 ambient temperature at the facility between the winter and the summer seasons. A negligible
203 influence of this temperature variation on the removal efficiency was observed. The
204 composition of the industrial emission was analyzed by GC from 6 samples collected during
205 the entire experimental period; the only organic detected compound with a remarkable
206 concentration was styrene (> 98% wt). The styrene concentrations at the waste gases were
207 quite variable influenced by the production pattern of the factory varying from 40 to 350 mg
208 Nm^{-3} . One typical styrene emission pattern over a working week is shown in Figure 2. The
209 styrene concentrations in the waste gas emissions for the one-year experiment were classified
210 into three groups depending on the factory workload: low production, normal production and
211 high production (Table 2). As can be seen, the styrene concentrations in a normal production
212 day (67% of the working period) ranged from 80 to 190 mg Nm^{-3} . The average concentration
213 with the standard deviation for the whole data of the three groups was 145 ± 58 mg Nm^{-3} .

214

215 3.2 Pilot plant performance

216 After inoculation (day 0), the BTF was operated during 4 months at three different
217 EBRTs: 66, 42 and 31 s (Stage I). The performance of the system along this stage is shown in
218 Figure 3, where the evolution with time of the IL and the RE is plotted. Following

219 inoculation, the operational conditions were selected to enhance the adaptation of the
220 microorganisms coming from the activated sludge inoculum to the new environment rich in
221 styrene, so that EBRT was set at 66 s, the highest tested. A progressive increase in RE was
222 achieved during the first operational week, 75% was reached on day 8 with an IL of 16 g m^{-3}
223 h^{-1} . However, from that day the efficiency gradually decreased to ~40% on day 21, coinciding
224 with the lowest IL ($\sim 6 \text{ g m}^{-3} \text{ h}^{-1}$). This fact was attributed to the low specialization of the
225 inoculum in styrene degradation since it came from an urban waste water treatment plant, thus
226 such low styrene loads didn't enhance the development of enough amount of styrene
227 degraders. In our previous experiments at laboratory, stable REs higher than 90% were
228 achieved since day 7 after inoculation with similar biomass and working with similar EBRT
229 and at IL of $12 \text{ g m}^{-3} \text{ h}^{-1}$ (Pérez et al., 2015). The difference between the results at laboratory
230 and in the on-site testing points out that the industrial units demand a longer adaptation period
231 to successfully handle the fluctuating and oscillating industrial emissions. At day 28, after 7
232 days with ILs between 10 and $23 \text{ g m}^{-3} \text{ h}^{-1}$, REs of ~70% were recovered, which could be
233 explained by a greater growth of specialized microorganisms when more amount of styrene
234 was available. From day 29 to 45 the air flow rate was increased to set an EBRT of 42 s and
235 the BTF reached an average RE of $76\% \pm 10\%$ (average IL of $14 \pm 5 \text{ g m}^{-3} \text{ h}^{-1}$) with a
236 maximum RE of 90% at day 37. After changing the EBRT to 31 s on day 45, an average RE
237 of $64\% \pm 10\%$ (average IL of $16 \pm 4 \text{ g m}^{-3} \text{ h}^{-1}$) with a fluctuating efficacy between 48% (on
238 day 76 with an IL of $21 \text{ g m}^{-3} \text{ h}^{-1}$) and 82% (on day 110 with an IL of $16 \text{ g m}^{-3} \text{ h}^{-1}$). The
239 observed fluctuating BTF performance can be also attributed to the variability of
240 concentration in the inlet waste gas associated to the changes in the manufacturing pattern.

241 In Stage II, the EBRT was kept constant at 31 s for 8 months to study the long term
242 performance under fluctuating and oscillating styrene emissions. As an example, the
243 evolution with time of IL and RE is shown in Figure 4 for the last two months. The BTF

244 reached an average RE of $80\% \pm 9\%$ with an average IL of $13 \pm 5 \text{ g m}^{-3} \text{ h}^{-1}$. The RE varied
245 between a minimum value of 63% (on day 345 with an IL of $15.5 \text{ g m}^{-3} \text{ h}^{-1}$) and a maximum
246 value of 94% (on day 306 with an IL of $11 \text{ g m}^{-3} \text{ h}^{-1}$). These data are better than those
247 obtained at 31 s of EBRT 8 months ago. The average RE increased from 64% (Stage I) to
248 80% (Stage II). In addition, the RE fluctuated in greater values in Stage II (from 63% to 94%)
249 in comparison with the variation range in Stage I (from 48% to 82%). This result could be
250 attributed to the development of a more stable biofilm, with more abundance of
251 microorganism able to degrade styrene, due to the application of moderate styrene loads
252 during a long period. Similar phenomenon was observed by Webster et al. (1999) in the
253 styrene removal by a pilot BTF. In that work, by artificially increasing the styrene load, EC
254 increased from $15 \text{ g m}^{-3} \text{ h}^{-1}$ to $24 \text{ g m}^{-3} \text{ h}^{-1}$ due to the fact that more quantity of biomass was
255 established after 160 days. Therefore, biotrickling filtration seems to require a long period to
256 achieve a stable performance under fluctuating and discontinuous styrene emissions, being
257 this one of special relevance for the scale-up of biotreatments from lab data.

258 Regarding the trickling water quality, it was analyzed twice per month obtaining
259 average values of 7.4 ± 0.5 of pH and $2.4 \pm 0.8 \text{ mS cm}^{-1}$ of conductivity for the whole study.
260 Ammonium and phosphate concentrations were higher than 10 mgN L^{-1} and 25 mgP L^{-1} ,
261 respectively. The soluble COD concentrations kept below 100 mg L^{-1} , thus the removed
262 pollutant with the purge represented less than 1% of the total amount of styrene feeding, so it
263 was assumed negligible for the evaluation of the BTF performance. The pressure drop of the
264 bed was $<20 \text{ Pa m}^{-1}$ for the whole experimental period.

265 The relationship between EC and IL at the three tested EBRT (31, 42 and 66 s) are
266 plotted in Figure 5 (a). Data at 31 s have been drawn for Stage II. Laboratory data from
267 previous experiment with similar operational conditions (EBRTs and IL) have been also
268 included (Pérez et al., 2015) in Figure 5 (a) for comparative purposes. Additionally, the

269 variation of the RE vs the IL for the data of the pilot unit in Stage II is shown in Figure 5 (b).
270 The EC and RE usually decrease when the EBRT is reduced for a constant IL. From the
271 results of this study, it can be observed an opposite trend since better results were achieved at
272 31 s (months 11 and 12 of operation) instead of at 66 s or 45 s (first two months). For
273 example, at ILs lower than $12 \text{ g m}^{-3} \text{ h}^{-1}$ near complete removal can be observed for 31 s
274 whereas REs values around 70% and between 40 and 70% were found for 42 and 66 s,
275 respectively. This behavior can be attributed to the low development of styrene degrading
276 microorganisms under industrial conditions. This lower biomass growth can also explain why
277 the outcomes of the pilot unit at 66 s differed from the lab data whereas results from both
278 systems matched for 31 s of residence time. For instance, the pilot unit reached an EC of 11.7
279 $\text{g m}^{-3} \text{ h}^{-1}$ (IL of $15.6 \text{ g m}^{-3} \text{ h}^{-1}$) versus an EC of $12.4 \text{ g m}^{-3} \text{ h}^{-1}$ (IL of $13.6 \text{ g m}^{-3} \text{ h}^{-1}$) obtained at
280 the lab at 66 s. However, quite similar performance was observed at 31 s with EC of 18.8 g m^{-3}
281 h^{-1} (IL of $24.9 \text{ g m}^{-3} \text{ h}^{-1}$) and $17.7 \text{ g m}^{-3} \text{ h}^{-1}$ (IL of $23.5 \text{ g m}^{-3} \text{ h}^{-1}$) for pilot and lab studies,
282 respectively. By running this long term experiment it is shown that the dynamic of growth of
283 styrene degraders plays a key role to achieve high efficiencies at industrial scale, being this
284 factor of greater importance than the contact time.

285 The results obtained in Stage II at 31 s can be considered as operational representative
286 data when an active biofilm has been developed, so it could be used for scale-up purposes. It
287 can be highlighted two inlet loads for (i) removals higher than 90%, at an IL up to $12 \text{ g m}^{-3} \text{ h}^{-1}$
288 with an EC of $11.2 \text{ g m}^{-3} \text{ h}^{-1}$ (RE of 93%); and for (ii) the highest observed elimination
289 capacity, at an IL of $24.9 \text{ g m}^{-3} \text{ h}^{-1}$ with an EC of $18.8 \text{ g m}^{-3} \text{ h}^{-1}$ (RE of 76%). Rene et al.
290 (2009) found a maximum EC of $382 \text{ g m}^{-3} \text{ h}^{-1}$ at an IL of $464 \text{ g m}^{-3} \text{ h}^{-1}$ (RE of 82%) in a
291 biofilter inoculated with the fungus *Sporothrix* sp. working at an EBRT of 120 s an inlet
292 concentrations ranged from 0.03 and 17.3 g m^{-3} . The critical load depending on the EBRT
293 was $196 \text{ g m}^{-3} \text{ h}^{-1}$ and $260 \text{ g m}^{-3} \text{ h}^{-1}$ at 20 and 120 s, respectively. Although the reported

294 elimination capacity working in the laboratory were much high, this is the first study
295 operating a BTF pilot plant at an EBRT as low as 31 s for controlling styrene at industrial air
296 emissions. In this context, Webster et al. (1999) obtained a slightly better EC of $24 \text{ g m}^{-3} \text{ h}^{-1}$
297 (RE 70 – 85%) in a BTF pilot, but working with an EBRT threefold higher (86 s). working a
298 BTF pilot at an EBRT threefold higher (86 s). Therefore, this would imply a three times
299 higher bioreactor for treating similar concentrations in the waste gas emissions, which mainly
300 depends on the manufacturing process emitting VOCs.

301 3.3 Performance of the combined system: Photocatalytic reactor and BTF pilot unit

302 After a year of testing, the UV photocatalytic reactor was coupled to the BTF pilot unit
303 as pretreatment of the styrene emissions prior to their treatment in the biological process. UV
304 reactor and BTF were operated at a residence time of 10 and 31 s respectively. The combined
305 system was evaluated during one week and the average performance results are summarized
306 in Table 3. The combined system achieved efficiencies around 77% at IL $\sim 16 \text{ g m}^{-3} \text{ h}^{-1}$.
307 Comparing this performance with the data of the pilot unit without UV photocatalytic
308 pretreatment shown in Figure 5 (b), it can be seen that the combined system is within the
309 operating variation range of the standalone BTF. This fact can be explained by the quite low
310 removal efficiencies obtained independently for the photocatalytic reactor, around 5%. This
311 low efficiency is in contradiction with those obtained with other aromatic compounds such
312 toluene, xylenes or ethylbenzene (Hinojosa-Reyes et al., 2012; Mohseni and Zhao, 2006;
313 Moussavi and Mohseni, 2007; Palau et al., 2012, 2011; Wei et al., 2010), for which it can be
314 considered a well-established technology. Results suggest that under the tested operational
315 conditions the TiO_2 -glass fiber supported catalyst was deactivated, which was corroborated by
316 visual inspection at the end of the test (brown color appeared). Literature data confirm that the
317 by-products of the photocatalytic oxidation of styrene can block the active catalyst sites
318 (Krichevskaya and Preis, 2003). These authors found an influence of the temperature and

319 humidity on the deactivation time, with an entire restoration of the photocatalytic activity
320 after 2 h of UV-irradiation passing clean airflow with 50% of relative humidity due to the
321 oxidation of the by-products. Therefore, a potential solution could be the use of an air
322 humidification step prior to the photocatalytic reactor to enhance the oxidation of the by-
323 product, although more studies are necessary for evaluating this technique as pretreatment of
324 biological processes in the fiber reinforced plastic industry.

325

326 3.4 Economical aspects

327 The economic feasibility of biotrickling filtration for the control of styrene emissions
328 in the fiber reinforced plastics industry was carried out by using a standard emission flow rate
329 of 30 000 Nm³ h⁻¹ and an average styrene concentration of 145 mg Nm⁻³. For sizing
330 calculations, it was decided to select a safety contact time of 45 s based on the experimental
331 results of the pilot unit in which at 31 s styrene loads up to 12 g m⁻³ h⁻¹ could be treated with
332 RE~90%. The estimations for the direct total costs excluding capital recovery are summarized
333 in Table 4. The annual costs are presented in terms of annualized cost per volumetric air flow
334 to be treated (€ year⁻¹ Nm⁻³ h). A comparison with the regenerative catalytic oxidizer (RCO)
335 combined with a zeolite rotor as pre-concentrator step is also included in Table 4. The
336 installation of a zeolite rotor concentrator reduces the consumption of natural gas with a net
337 positive impact on the viability of the thermal treatment option for diluted emissions of
338 VOCs. The electricity cost has been estimated by the power of the blower calculated from the
339 required pressure drop in each case (10 kW for the BTF and 25kW for the RCO) and with an
340 EU average electricity price of 0.12 € kWh⁻¹ (Eurostat, 2016). The consumption of natural gas
341 (energy content of 9.6 kWh Nm⁻³) has been calculated using an EU average price of 0.355 €
342 Nm⁻³ (Eurostat, 2016) and an energy recovery of 95%. Capital costs of biological and thermal
343 system are similar, approximately 1.3 – 1.5 € per year and per Nm³ h⁻¹ (assuming 10 years of

344 equipment life), so capital recovery has not been included for comparative purposes. Indirect
345 annual cost, excluding capital recovery, has been estimated as 10% of the direct annual cost.

346 Results show that the total direct cost for the biological system, 0.71 € per year and per
347 $\text{Nm}^3 \text{h}^{-1}$, is approximately 3 times lower than that estimated for the regenerative catalytic
348 oxidizer combined with a zeolite pre-concentrator, 2.27 € per year and per $\text{Nm}^3 \text{h}^{-1}$. The total
349 direct cost for the BTF in this study expressed as 1.0 € per 10 000 m^3 of air treated are
350 comparable to previously reported operational costs of BTF treating VOC emissions in
351 different industrial sectors. For example, Boswell et al. (2010) estimated operational costs
352 above 2 \$ per 10 000 m^3 of air treated in a biotreatments installed in a panel board factory.
353 Álvarez-Hornos et al. (2011) reported 2 € of operational costs per 10 000 m^3 of air treated in a
354 BTF treating emissions from a plastic-coating facility and Lafita et al. (2012a) obtained
355 operational cost ranging from 3 to 10 € per 10 000 m^3 of air treated in a wood-coating factory.
356 So, biotrickling filter provides a low-cost and efficient solution for VOC control of air
357 emissions, especially in tropical countries where there are warm temperatures that would
358 enhance the aerobic biodegradation.

359 **Conclusions**

360 The biological removal of industrial air emissions of styrene coming from a facility
361 manufacturing fiber reinforced composite profiles was studied for one year by using a BTF
362 pilot unit. The styrene emissions exhibited variable pattern related to fluctuating and
363 discontinuous emissions with an average styrene concentration of $145 \pm 58 \text{ mg Nm}^{-3}$. Under
364 these industrial conditions, it was necessary several months to develop a stable biofilm
365 containing enough microorganisms able to degrade styrene. Therefore, better results were
366 obtained at the last months of operation, thus being comparable with previous laboratory data
367 for the tested styrene loads. This work shows that at the lowest residence time found in
368 literature (31 s) for treating industrial air emissions of styrene 93% of removal was achieved

369 at an IL of $12 \text{ g m}^{-3} \text{ h}^{-1}$. The highest elimination capacity was found on $18.8 \text{ g m}^{-3} \text{ h}^{-1}$ at an IL
370 of $24.9 \text{ g m}^{-3} \text{ h}^{-1}$. The total direct cost, excluding capital recovery, for the BTF was estimated
371 to be 3 times lower than that for the regenerative catalytic oxidizer combined with a zeolite
372 pre-concentrator. A UV-photocatalytic reactor was tested as pretreatment of the biological
373 process. Very low efficiencies in the photoreactor occurred due to the deactivation of the
374 catalyst, thus more research on catalyst regeneration is needed for evaluating photocatalysis as
375 pretreatment for these industrial emissions. Spite of these results, photodegradation of VOCs,
376 especially in tropical countries with sufficient sunlight, appears as an emergent technology
377 that could combine with biotreatments to improve the elimination capacities per unit of
378 volume.

379

380 **Acknowledgements**

381

382 The research leading to these results has received funding from the People Programme (Marie
383 Curie Actions) of the European Union's Seventh Framework Programme FP7/2007-2013/
384 under *REA* grant agreement n° 284949. Authors gratefully acknowledge the financial support
385 by Ministerio de Economía y Competitividad (Project CTM2014-54517-R co-financed with
386 FEDER funds). We would like to thank Dr. C. Lafita and Dr. J. Palau for their support in the
387 maintenance tasks of the pilot plant. The authors would like to give special thanks to Exel
388 Composites and Pure Air Solutions for their constant collaboration and support.

389

390 **References**

391

392 Álvarez-Hornos, F.J., Lafita, C., Martínez-Soria, V., Penya-Roja, J.M., Pérez, M.C.,
393 Gabaldón, C., 2011. Evaluation of a pilot-scale biotrickling filter as a VOC control
394 technology for the plastic coating sector. *Biochem. Eng. J.* 58-59, 154–161.
395 <http://dx.doi.org/10.1016/j.bej.2011.09.009>.

396 Arnold, M., Reittu, A., von Wright, A., Martikainen, P.J., Suihko, M.L., 1997. Bacterial
397 degradation of styrene in waste gases using a peat filter. *Appl. Microbiol. Biotechnol.* 48,
398 738–44. <http://dx.doi.org/10.1007/s002530051126>.

399 Boswell, J., 2010. Understanding biofilters: the promise of a reduced energy profile has
400 increased interest in biofiltration of air pollutants. But going bio is a lot more
401 complicated than simply replacing a thermal oxidizer. *Pollut. Eng.* February 1, 14–18.

402 Cheng, Z.W., Zhang, L.L., Chen, J.M., Yu, J.M., Gao, Z.L., Jiang, Y.F., 2011. Treatment of
403 gaseous alpha-pinene by a combined system containing photo oxidation and aerobic
404 biotrickling filtration. *J. Hazard. Mater.* 192, 1650–1658.
405 <http://dx.doi.org/10.1016/j.jhazmat.2011.06.092>.

406 Dehghanzadeh, R., Torkian, A., Bina, B., Poormoghaddas, H., Kalantary, A., 2005.
407 Biodegradation of styrene laden waste gas stream using a compost-based biofilter.
408 *Chemosphere* 60, 434–439. <http://dx.doi.org/10.1016/j.chemosphere.2004.12.003>.

409 Den, W., Ravindran, V., Pirbazari, M., 2006. Photooxidation and biotrickling filtration for
410 controlling industrial emissions of trichloroethylene and perchloroethylene. *Chem. Eng.*
411 *Sci.* 61, 7909–7923. <http://dx.doi.org/10.1016/j.ces.2006.09.015>.

412 Derwent, R.G., Jenkin, M.E., Saunders, S.M., Pilling, M.J., 1998. Photochemical ozone
413 creation potentials for organic compounds in northwest Europe calculated with a master

414 chemical mechanism. *Atmos. Environ.* 32, 2429–2441.
415 [http://dx.doi.org/10.1016/S1352-2310\(98\)00053-3](http://dx.doi.org/10.1016/S1352-2310(98)00053-3).

416 Di Tomasso, C., Gombos, Z.J., Summerscales, J., 2014. Styrene emissions during gel-coating
417 of composites. *J. Clean. Prod.* 83, 317–328.
418 <http://dx.doi.org/10.1016/j.jclepro.2014.07.051>.

419 European Commission, 2002. European union risk assessment report “Styrene, part I –
420 environment”. European Chemical Bureau, Italy.

421 Eurostat, 2016. Electricity and natural gas price statistics. Online at
422 [http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics#Elec](http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics#Electricity_prices_for_industrial_consumers)
423 [tricity_prices_for_industrial_consumers](http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_price_statistics#Electricity_prices_for_industrial_consumers). (accessed 7.15.16).

424 Halecky, M., Paca, J., Kozliak, E., Jones, K., 2016. Effect of loading types on performance
425 characteristics of a trickle-bed bioreactor and biofilter during styrene/acetone vapor
426 biofiltration. *J. Environ. Sci. Heal. Part A* 4529, 1–10.
427 <http://dx.doi.org/10.1080/10934529.2016.1159882>.

428 Hinojosa-Reyes, M., Rodríguez-González, V., Arriaga, S., 2012. Enhancing ethylbenzene
429 vapors degradation in a hybrid system based on photocatalytic oxidation UV/TiO₂–In
430 and a biofiltration process. *J. Hazard. Mater.* 209, 365–371.
431 <http://dx.doi.org/10.1016/j.jhazmat.2012.01.035>.

432 Jianming, Y., Wei, L., Zhuowei, C., Yifeng, J., Wenji, C., Jianmeng, C., 2014.
433 Dichloromethane removal and microbial variations in a combination of UV pretreatment
434 and biotrickling filtration. *J. Hazard. Mater.* 268, 14–22.
435 <http://dx.doi.org/10.1016/j.jhazmat.2013.12.068>.

436 Krichevskaya, M., Preis, S., 2003. Gas-phase photocatalytic oxidation of styrene in a simple

437 tubular TiO₂ reactor. *J. Adv. Oxid. Technol.* 6, 150–157.

438 Kuhn, D., Kholiq, M.A., Heinzle, E., Bühler, B., Schmid, A., 2010. Intensification and
439 economic and ecological assessment of a biocatalytic oxyfunctionalization process.
440 *Green Chem.* 12, 815. <http://dx.doi.org/10.1039/b921896c>.

441 Lackey, L., Gamble, J., Holt, M., 1998. Feasibility testing of biofiltration technology for
442 remediating air contaminated by a boat manufacturing facility. *J. Air Waste Manage.*
443 *Assoc.* 48, 527–536. <http://dx.doi.org/10.1080/10473289.1998.10463708>.

444 Lafita, C., Peña-Roja, J.M., Gabaldón, C., Martínez-Soria, V., 2012a. Full-scale biotrickling
445 filtration of volatile organic compounds from air emission in wood-coating activities. *J.*
446 *Chem. Technol. Biotechnol.* 87, 732–738. <http://dx.doi.org/10.1002/jctb.3716>.

447 Lafita, C., Peña-Roja, J.M., Sempere, F., Waalkens, A., Gabaldón, C., 2012b. Hydrogen
448 sulfide and odor removal by field-scale biotrickling filters: influence of seasonal
449 variations of load and temperature. *J. Environ. Sci. Health. A. Tox. Hazard. Subst.*
450 *Environ. Eng.* 47, 970–978. <http://dx.doi.org/10.1080/10934529.2012.667302>.

451 Miller, R.R., Newhook, R., Poole, A., 1994. Styrene production, use, and human exposure.
452 *Crit. Rev. Toxicol.* 24, 1–10. <http://dx.doi.org/10.3109/10408449409020137>.

453 Mohseni, M., Zhao, J.L., 2006. Coupling ultraviolet photolysis and biofiltration for enhanced
454 degradation of aromatic air pollutants. *J. Chem. Technol. Biotechnol.* 81, 146–151.
455 <http://dx.doi.org/10.1002/jctb.1371>.

456 Moussavi, G., Mohseni, M., 2007. Using UV pretreatment to enhance biofiltration of
457 mixtures of aromatic VOCs 144, 59–66.
458 <http://dx.doi.org/10.1016/j.jhazmat.2006.09.086>.

459 Novak, V., Paca, J., Halecky, M., Soccol, C.R., 2008. Styrene biofiltration in a trickle-bed

460 reactor. *Brazilian Arch. Biol. Technol.* 51, 385–390.
461 <http://dx.doi.org/10.1590/S1516-89132008000200019>.

462 Palau, J., Peña-Roja, J.M., Gabaldón, C., Álvarez-Hornos, F.J., Sempere, F., Martínez-Soria,
463 V., 2011. UV photocatalytic oxidation of paint solvent compounds in air using an
464 annular TiO₂-supported reactor. *J. Chem. Technol. Biotechnol.* 86, 273–281.
465 <http://dx.doi.org/10.1002/jctb.2515>.

466 Palau, J., Peña-Roja, J.M., Gabaldón, C., Álvarez-Hornos, F.J., Martínez-Soria, V., 2012.
467 Effect of pre-treatments based on UV photocatalysis and photo-oxidation on toluene
468 biofiltration performance. *J. Chem. Technol. Biotechnol.* 87, 65–72.
469 <http://dx.doi.org/10.1002/jctb.2683>.

470 Pérez, M.C., Álvarez-Hornos, F.J., Portune, K., Gabaldón, C., 2015. Abatement of styrene
471 waste gas emission by biofilter and biotrickling filter: comparison of packing materials
472 and inoculation procedures. *Appl. Microbiol. Biotechnol.* 99, 19–32.
473 <http://dx.doi.org/10.1007/s00253-014-5773-9>.

474 Rene, E.R., Veiga, M.C., Kennes, C., 2009. Performance of a biofilter for the removal of high
475 concentrations of styrene under steady and non-steady state conditions. *J. Hazard. Mater.*
476 168, 282–290. <http://dx.doi.org/10.1016/j.jhazmat.2009.02.032>.

477 Rene, E.R., Al Momani, F.A., Veiga, M.C., Kennes, C., 2011. Removal of dichloromethane
478 vapours in an integrated bioreactor-photoreactor. In: Kennes, C., Veiga, M.C., (Eds.),
479 Proceedings of the 4th International Conference on Biotechniques for Air Pollution
480 Control and Bioenergy, La Coruña, Spain, pp. 205–209.

481 Runye, Z., Kennes, C., Zhuowei, C., Lichao, L., Jianming, Y., Jianmeng, C., 2015. Styrene
482 removal in a biotrickling filter and a combined UV-biotrickling filter: Steady- and

483 transient-state performance and microbial analysis. *Chem. Eng. J.* 275, 168–178.
484 <http://dx.doi.org/10.1016/j.cej.2015.04.016>.

485 Saucedo-Lucero, J.O., Arriaga, S., 2015. Photocatalytic oxidation process used as a
486 pretreatment to improve hexane vapors biofiltration. *J. Chem. Technol. Biotechnol.* 90,
487 907–914. <http://dx.doi.org/10.1002/jctb.4396>.

488 Sempere, F., Martínez-Soria, V., Palau, J., Peña-Roja, J.M., San-Valero, P., Gabaldón, C.,
489 2011. Effects of nitrogen source and empty bed residence time on the removal of styrene
490 gaseous emissions by biotrickling filtration. *Bioprocess Biosyst. Eng.* 34, 859–67.
491 <http://dx.doi.org/10.1007/s00449-011-0536-9>.

492 Sempere, F., Martínez-Soria, V., Peña-Roja, J.M., Waalkens, A., Gabaldón, C., 2012.
493 Control of VOC emissions from a flexographic printing facility using an industrial
494 biotrickling filter. *Water Sci. Technol.* 65, 177–182.
495 <http://dx.doi.org/10.2166/wst.2011.839>.

496 United States environmental protection agency (USEPA), 1994. OPPT fact sheets, styrene
497 fact sheets: support document.

498 Wang, C., Xi, J.-Y., Hu, H.-Y., Yao, Y., 2009. Advantages of combined UV
499 photodegradation and biofiltration processes to treat gaseous chlorobenzene. *J. Hazard.*
500 *Mater.* 171, 1120–1125. <http://dx.doi.org/10.1016/j.jhazmat.2009.06.129>.

501 Webster, T.S., Cox, H.H.J., Deshusses, M.A., 1999. Resolving operational and performance
502 problems encountered in the use of a pilot/full-scale biotrickling fiber reactor. *Environ.*
503 *Prog.* 18, 162–172. <http://dx.doi.org/10.1002/ep.670180312>.

504 Wei, Z., Sun, J., Xie, Z., Liang, M., Chen, S., 2010. Removal of gaseous toluene by the
505 combination of photocatalytic oxidation under complex light irradiation of UV and

506 visible light and biological process. *J. Hazard. Mater.* 177, 814–821.
507 <http://dx.doi.org/10.1016/j.jhazmat.2009.12.106>.

508 Witten, E., Thomas, M., Michael, K., 2015. Composites market report 2015. *Ind. Verstärkte*
509 *Kunststoffe*, online at <http://www.eucia.eu/news/composites-market-report-2015/>.
510 (accessed 7.15.16).

511 Zhang, J., Li, L., Liu, J., Han, Y., 2016. Temporal variation of microbial population in
512 acclimation and start-up period of a thermophilic desulfurization biofilter. *Int.*
513 *Biodeterior. Biodegrad.* 109, 157–164. <http://dx.doi.org/10.1016/j.ibiod.2016.01.021>.

514

515 **Table 1** Recent examples of VOC removal by combining UV photodegradation pretreatment with biotreatments.

Pollutant	Pretreatment ^a	τ^b , s	Biotreatment ^a	EBRT, s	C_{in}^c , $g\ m^{-3}$	IL, $g\ m^{-3}\ h^{-1}$	EC_{max}^d , $g\ m^{-3}\ h^{-1}$	RE, %	Reference
Chlorobenzene	PTO	24 – 81	BF	41 – 122	0.25 – 1.5	-	60	-	Wang et al., 2009
Dichloromethane	TiO ₂ -PCA	55.2	BTF	120	0.5 – 5.6	-	268	89	Rene et al., 2011
Dichloromethane	PTO	10	BTF	36	0.4 – 0.6	-	68.5	>66	Jianming et al., 2014
Ethylbenzene	TiO ₂ - PCA	30	BF	30	0.5 – 7.5	450	275	61	Hinojosa-Reyes et al., 2012
n-Hexane	ZnO- PCA	60	BF	30.4	-	200	43	-	Saucedo-Lucero and Arriaga, 2014
Perchloroethylene	PTO	6 – 36	BTF	120	5 – 45 ^e	-	-	>99	Den et al., 2006
α -pinene	PTO	18	BTF	17	0.6 – 1.5	-	94.2	-	Cheng et al., 2011
Styrene	PTO	10	BTF	30	0.5 – 4.0	478	309	-	Runye et al., 2015
Toluene	PTO	0.5 – 1.5	BF	30 – 45	0.07 – 0.65	48	48	-	Moussavi and Mohseni, 2007
Toluene	N-TiO ₂ /zeolite PCA	-	BF	-	0.2 – 0.5	-	-	96.7	Wei et al., 2010
Toluene	TiO ₂ - PCA	2.7	BF	44.5	-	110	93.2	-	Palau et al., 2012
Trichloroethylene	PTO	6 – 36	BTF	120	25 – 350 ^e	-	-	>99	Den et al., 2006
o-Xylene	PTO	0.5 – 1.2	BF	35 – 75	-	20	20	-	Mohseni and Zhao, 2006
o-Xylene	PTO	0.5 – 1.5	BF	30 – 45	0.07 – 0.65	46	46	-	Moussavi and Mohseni, 2007

516 ^a PTO: Photoreactor, PCA: Photocatalytic reactor, BF: Biofilter, BTF: Biotrickling filter. ^b τ , residence time in the photoreactor. ^c C_{in} , inlet
517 pollutant concentration. ^d EC_{max} , maximum EC. ^e Concentrations in ppm_v.

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522 **Table 2** Variability of styrene concentration in the waste gases treated in the BTF pilot unit.

Factory Workload	Frequency, %	Styrene Concentration, mg Nm⁻³
Low production	17	40 – 80
Normal production	67	80 – 190
High production	16	190 – 350

523

524

525 **Table 3** Performance of the combined system (Photocatalytic reactor and BTF pilot unit).

526 Average values \pm SD.

Combined System	
IL, $\text{g m}^{-3} \text{h}^{-1}$	15.9 ± 2.2
RE, %	$77\% \pm 5\%$
EC, $\text{g m}^{-3} \text{h}^{-1}$	12.3 ± 1.4

527

528

529 **Table 4** Comparison of the estimated total direct cost, excluding capital recovery, of the
 530 industrial-scale BTF with the zeolite rotor plus RCO configuration.

Biotrickling filter technology	
Direct annual cost ^a (€ year ⁻¹ Nm ⁻³ h)	
Operating labor ^b	0.07
Maintenance ^c	0.12
Utilities	
Electricity	0.29
Nutrients and chemicals	0.13
Tap water	0.03
Indirect annual cost ^d (€ year ⁻¹ Nm ⁻³ h)	0.07
Total direct cost (€ year ⁻¹ Nm ⁻³ h)	0.71
Zeolite rotor + RCO	
Direct annual cost (€ year ⁻¹ Nm ⁻³ h)	
Operating labor	0.07
Maintenance	0.12
Catalyst replacement ^e	0.22
Utilities	
Electricity	0.72
Natural gas	0.92
Indirect annual cost (€ year ⁻¹ Nm ⁻³ h)	0.22
Total direct cost (€ year ⁻¹ Nm ⁻³ h)	2.27

531 ^a Assumes 7,200 h year⁻¹. ^b 0.5 h d⁻¹ of operator at 15 €/h + 15% of supervisor. ^c 0.5 h d⁻¹ of operator +
 532 100% of maintenance labor as materials cost. ^d Includes overhead, administrative charges, taxes, and
 533 insurance. ^e 18 € m⁻³ for metal oxide + 10% of catalyst cost as labor cost for replacing catalyst,
 534 assuming 5 years of catalyst life.

535

536

537 **Figure Captions**

538 **Figure 1** Scheme of the pilot-scale BTF.

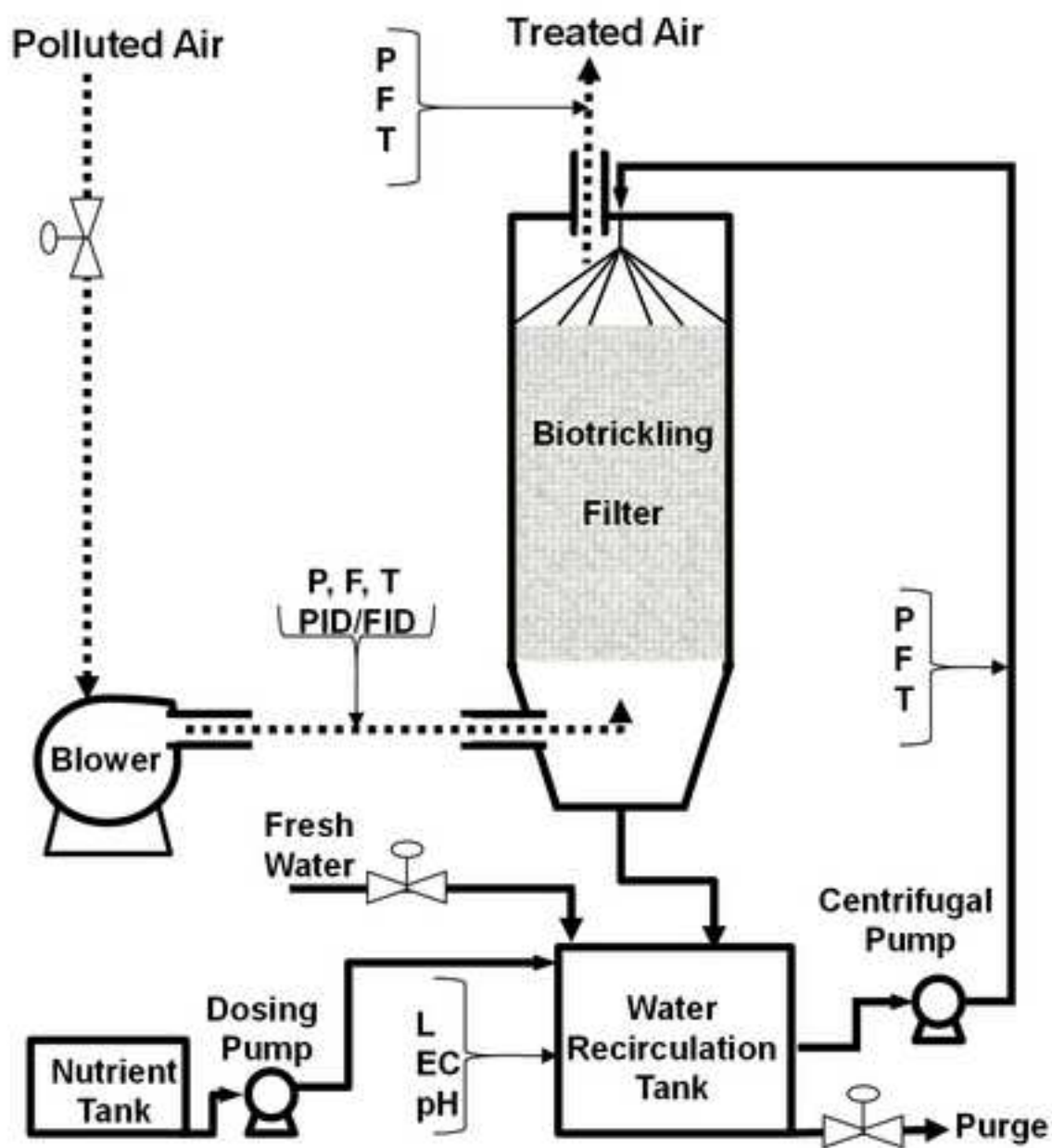
539 **Figure 2** Typical styrene emission pattern during a working week (Day 0: Monday 0:00 am).

540 **Figure 3** Evolution of the IL (solid triangle) and the RE (solid circle) in the BTF unit during
541 Stage I.

542 **Figure 4** Evolution of the IL (solid triangle) and the RE (solid circle) in the BTF unit during
543 Stage II.

544 **Figure 5** EC vs IL for different EBRTs in BTF pilot unit: 31 s (solid circle), 42 s (solid
545 square) and 66 s (solid triangle); and in previous laboratory experiment: 31 s (open circle), 45
546 s (open square) and 60 s (open triangle).

Figure1



Specification:

- P:** Pressure Detector (Pa)
- T:** Temperature Detector ($^{\circ}\text{C}$)
- F:** Flowrate Measurer (m^3/h)
- PID/FID:** VOC Concentration ($\text{mg C}/\text{m}^3$)
 - PID:** Photo Ionization Detector
 - FID:** Flame Ionization Detector
- L:** Liquid Level Detector
- EC:** Electrical Conductivity Detector

- Water line
-** Air line

Figure2

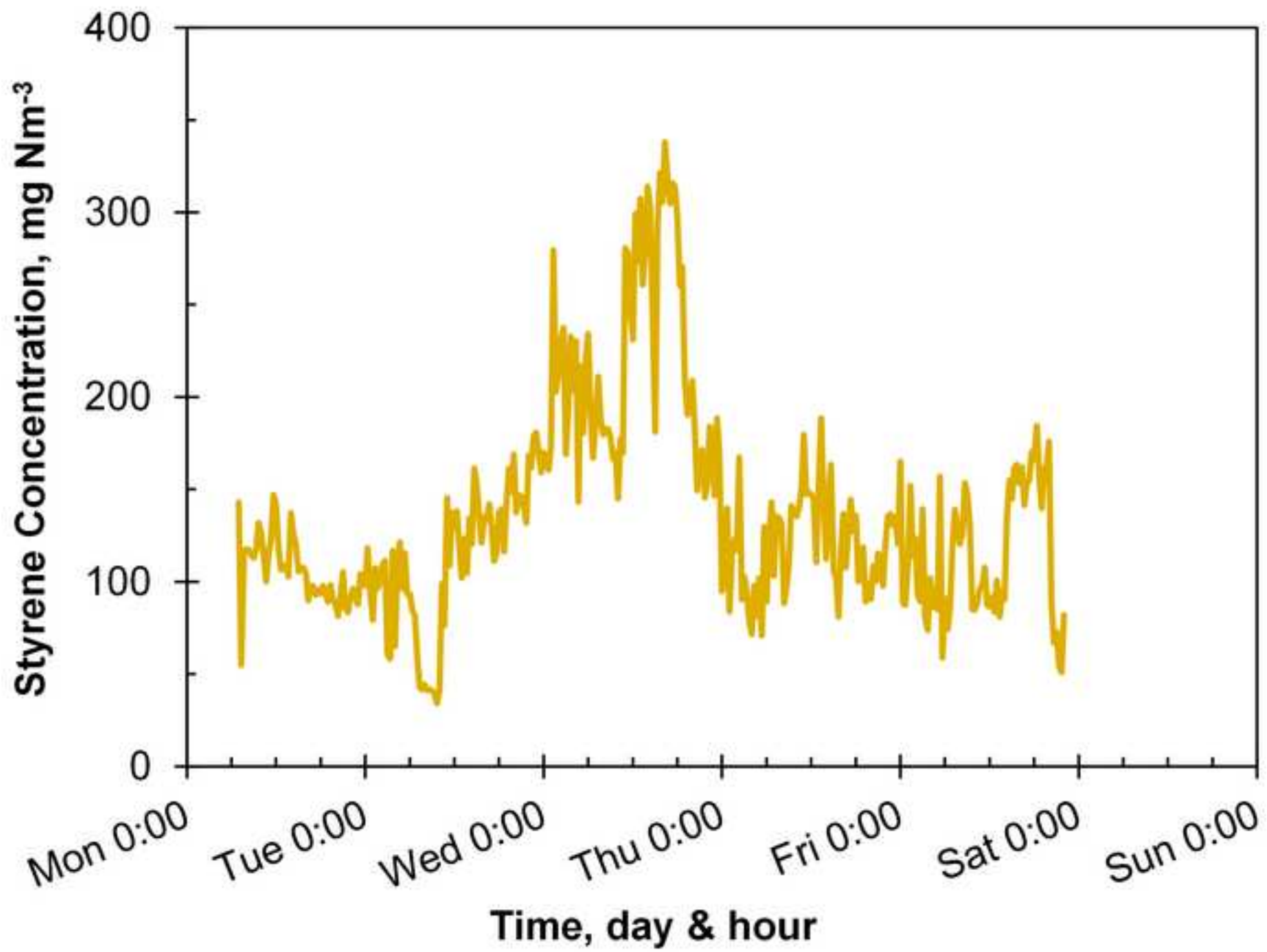


Figure3

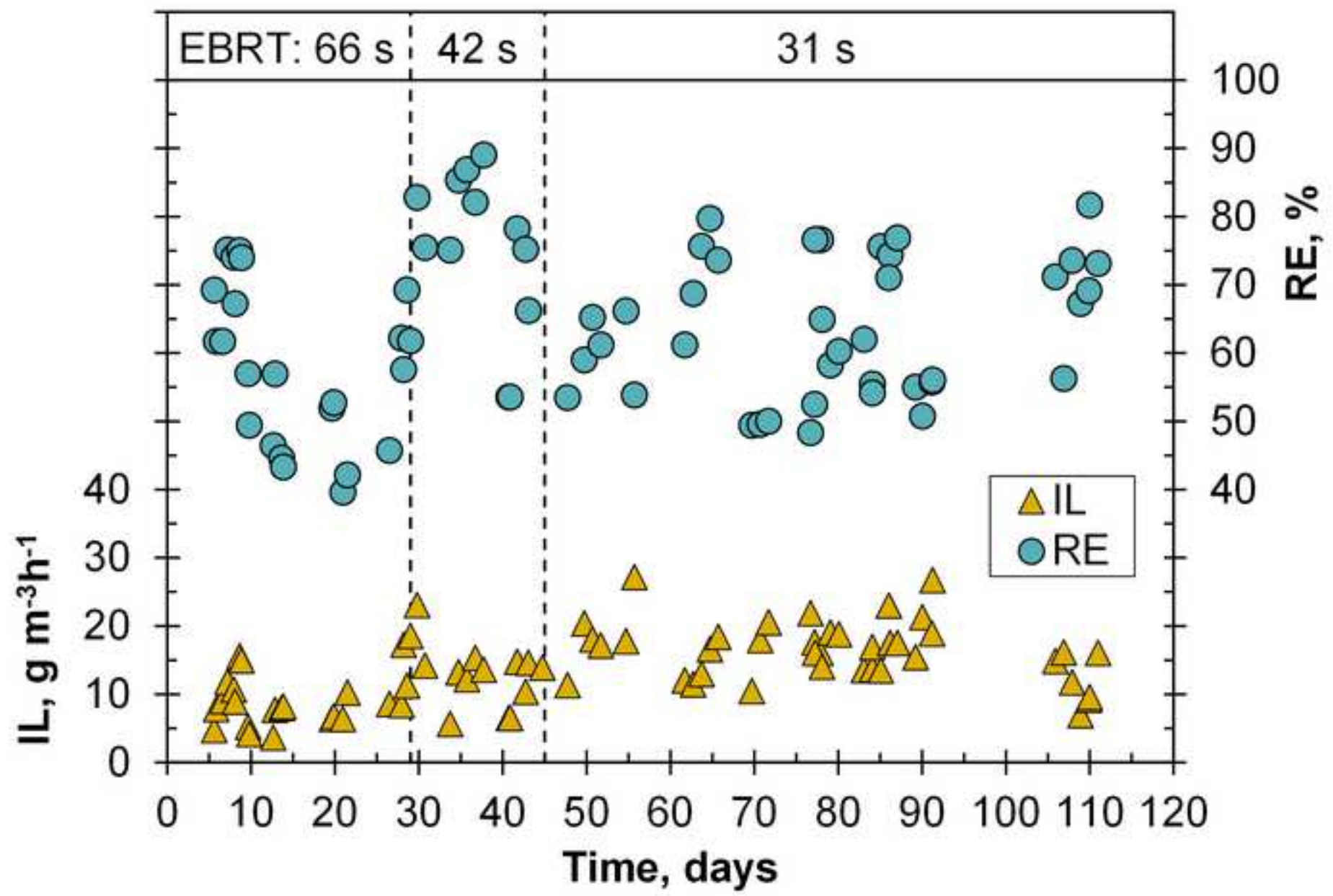


Figure4

