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1 **The architecture and metabolic traits of monospecific photosynthetic**  
2 **biofilms studied in a custom flow-through system**

3  
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14 **Running title:** architecture and physiology of microalgae biofilms

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51 **Abstract**

52 Microalgae biofilms have a great ecological importance and a high biotechnological potential.  
53 Nevertheless, an in-depth and combined structural (i.e. the architecture of the biofilm) and  
54 physiological characterization of microalgae biofilms is still missing. An approach able to  
55 provide at the same time physiological and structural information during biofilm growth  
56 would be of paramount importance to understand these complex biological systems and to  
57 optimize their productivity. In this study, monospecific biofilms of a diatom and a green alga  
58 were grown under dynamic conditions in custom flow cells represented by UV/Vis  
59 spectroscopic cuvettes. Such flow cells were conceived to characterize the biofilms by several  
60 techniques **mostly** *in situ* and in a non-destructive way. Physiological traits were obtained  
61 measuring variable chlorophyll *a* fluorescence by pulse amplitude modulated fluorometry  
62 (PAM) and by scanning the biofilms in a spectrometer to obtain *in vivo* pigments spectral  
63 signatures. The architectural features were obtained by imaging the biofilms with a confocal  
64 scanning laser microscope (CLSM) and an optical coherence tomograph (OCT). Overall, this  
65 experimental setup allowed us to follow the growth of two biofilm-forming microalgae  
66 showing that cell physiology is more affected in complex biofilms likely as a consequence of  
67 alterations in local environmental conditions.

68

69 **Keywords:** CLSM, flow cell, FTIR-spectroscopy, Microalgae biofilms, OCT, PAM

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71

72 **Introduction**

73 Microalgae biofilms play a crucial ecological role in most aquatic ecosystems as they  
74 contribute substantially to the primary production of shallow waters (Buhmann et al., 2012).  
75 In most coastal and estuarine areas, they also stabilize sediments and promote the formation  
76 of microbial communities essential for the functioning of the main biogeochemical cycles in  
77 such environments. With respect to their planktonic counterparts, microalgae biofilms present  
78 biomass densities that can be 10 to 100 times higher (Ozkan et al., 2012; Podola et al., 2017).  
79 Such characteristic can provide strong resistance to grazing and pollutants but it can also  
80 create very strong gradients of light and nutrients making them rapidly limiting in some  
81 locations within the biofilm (Battin et al., 2016). For biotechnological applications, the high  
82 productivity of microalgae biofilms has been recently recognized as a key advantage of  
83 biofilm-based systems over classical photo-bioreactors where microalgae are in the planktonic  
84 state (Berner et al., 2015; Gross et al., 2015).

85 Despite the importance of characterizing the physiology of photosynthetic biofilms, the  
86 majority of studies have been performed on mixed natural communities (e.g.  
87 microphytobenthic biofilms with several microalgae taxa and bacteria), and only few studies  
88 have investigated in parallel their physiology and architecture (i.e. specific 3D organization of  
89 cells and matrix components) (Mallick et al., 2020; Stiefelmaier et al., 2020; Wijihastuti et al.,  
90 2017). However, understanding how the metabolic activity of cells changes as biofilm 3D  
91 structure matures might help identifying key biofilm traits to better comprehend such a  
92 complex life style in nature and to optimize biotechnological processes. Nutrient limitation or  
93 light acclimation might be identified on the basis of chlorophyll *a* variable fluorescence  
94 (Beardall et al., 2001) or on the base of changes of specific macromolecular pools such as  
95 lipids and carbohydrates (Dean et al., 2010; Jebsen et al., 2012). Furthermore, the parallel  
96 study of both physiological and architectural biofilm traits might reveal structural-dependent  
97 changes or species-specific acclimation strategies in photosynthetic biofilms. In this context,  
98 the development of a system that allows measurements of 3D structures and physiological  
99 properties of microalgae biofilms is of great importance.

100 In order to simulate environmental conditions, biofilms are experimentally grown under  
101 dynamic conditions, typically reached by continuously pumping fresh medium into a flow cell  
102 where the biofilm is developing (Fanesi et al., 2021; Le Norcy et al., 2019). Several systems  
103 exist for the study of bacterial and photosynthetic biofilms (Buhmann et al., 2012; Forster and  
104 Martin-Jézéquel, 2005; Heydorn et al., 2000; Lemke et al., 2021; Wijihastuti et al., 2017;  
105 Zippel et al., 2007) but only few of them allow for multiple *in-situ* measurements. In this  
106 study, we developed a user friendly flow-through system that can be used to grow  
107 photosynthetic biofilms continuously under controlled laboratory conditions. The flow cell is  
108 conceived using a four-face clear spectrophotometer cuvette that allows to easily reproduce  
109 the system in different labs and to switch between several measurements modes. The system

110 was tested using two biofilm-forming microalgae (a diatom and a green algae) that produce  
111 biofilms with different architectural characteristics (Fanesi et al., 2019). Indeed, specific  
112 architectures may translate in the formation of light and nutrient gradients (including gases  
113 such as CO<sub>2</sub>) as a function of biofilm complexity (Battin et al., 2016; Schnurr and Allen,  
114 2015). We therefore tested the hypothesis that photosynthetic cells producing biofilms with  
115 high structural complexities (e.g. high thickness and cell abundances) may need to acclimate  
116 and change their physiological performances in order to optimize their fitness in the changing  
117 local conditions (Stewart and Franklin, 2008). A consequence of this hypothesis is that a thick  
118 biofilm would be expected to induce stronger gradients and therefore more changes in cell  
119 physiology with respect to a thinner biofilm where light and nutrients gradients are weaker  
120 and may impact less cell metabolic performances.

121 In order to test our hypothesis, the structural characteristics of photosynthetic biofilms were  
122 monitored by means of complementary techniques. Confocal Laser Scanning Microscopy  
123 (CLSM) at the microscopic scale and Optical Coherence Tomography (OCT) at the mesoscale  
124 allowing a higher penetration in the sample (Wagner and Horn, 2017). Photosynthetic  
125 efficiency was measured using a pulse amplitude modulated (PAM) fluorometer and pigments  
126 and macromolecules signatures were obtained using a UV-Visible and an ATR-FTIR  
127 spectrometer. All the techniques were chosen because they are non-destructive and **have the**  
128 **potential to** allow for *in situ* measurements.

129

## 130 **Materials and Methods**

### 131 *Planktonic culture maintenance*

132 The planktonic cultures of *Cylindrotheca closterium* AC170 (Caen, France) and *Chlorella*  
133 *vulgaris* SAG 211-12 (Göttingen, Germany) were grown in 250 mL Erlenmeyer flasks filled  
134 with 30 mL of growth medium (artificial sea water (Lyman and Fleming, 1940) + Walne's

135 medium (Walne, 1970)) for *C. closterium*, 3N-Bristol for *C. vulgaris* (Bischoff and Bold,  
136 1963) and were kept in the exponential phase by frequent re-inoculations (every 3 days). The  
137 cultures were continuously shaken and grown in an incubator at 25°C under a continuous  
138 photon flux density (PFD) of 20  $\mu\text{mol m}^{-2}\text{s}^{-1}$ .

139

#### 140 *Development of the cuvette flow-through system for biofilm cultivation*

141 A bottle of sterilized medium is connected to the flow cell, which is connected to a waste  
142 bottle using silicon tubes (I.D. 1mm). The medium is pumped inside the system by means of a  
143 multichannel peristaltic pump 205S/CA (Watson and Marlow; La Queue Lez Yvelines,  
144 France).

145 The innovative part of the flow-through incubation system conceived in this study is the use  
146 of a spectrophotometer cuvette (Fig. 1a,b). Such a flow cell was conceived using a four face  
147 clear cuvette made of poly(methyl methacrylate) (PMMA) (01961-00, Kartell S.p.A., Italy;  
148 total volume of 4mL; 1 cm optical path length), a plastic cap (XK25.1, Roth) and two  
149 connectors: one for the inflow medium was made from a glass capillary (micro-hematocrit  
150 capillary tubes, 1.2 mm I.D.) whereas the second was made from a 10 $\mu\text{L}$  pipet tip for the out  
151 flow. Two holes were made on the plastic cap (about 6-7 mm of distance). In one hole, the  
152 plastic tip was fitted in and in the second the glass capillary. The plastic tip has a length of  
153 about 10mm, 5 mm are inside the cuvette and 5mm are used to connect the silicone tube. The  
154 capillary was cut to a final length of 40mm: 35mm are inside the cuvette and 5mm are used to  
155 connect the silicon tube (Fig. 1a). The difference in length between the glass capillary and the  
156 plastic tip is necessary in order to avoid short circuit between the inflow and the outflow of  
157 medium. Once fitted in, the two connectors were sealed on the plastic cap using transparent  
158 silicon in order to avoid leakages. Once completed, the external edges of the cap were filled

159 with silicon and the whole cap inserted in the cuvette and the flow-through system was let dry  
160 overnight before using it for the experiments.

161 The optical characteristics and the standard design of the cuvette allow to perform *in situ* and  
162 in a non-destructive way measurements with multiple instruments. In our case, the choice of  
163 the measurements was done in order to get a complete characterization of biofilm structural,  
164 metabolic and compositional properties.

165

166 *Inoculum and mode of operation of the cuvette flow-through cell for photosynthetic biofilms*  
167 *growth*

168 Before each set of experiments, the complete system including the cuvette flow cells were  
169 sterilized by pumping a solution (0.5% v/v) of **commercial** bleach for two hours. The  
170 system was then washed with two liters of autoclaved MilliQ water and filled with the  
171 specific sterile growth media used for the two algae (see *planktonic culture* section).

172 For the inoculum of the system, an aliquot of planktonic culture containing  $5 \times 10^5$  cell/mL for  
173 *C. closterium* and  $10^6$  cell/mL for *C. vulgaris* were injected using an in-line luer injection port  
174 (Ibidi GmbH, Germany) placed just before the cuvette. The cuvette inlet and outlet were then  
175 closed with clips and were gently shaken by hand to obtain a homogeneous suspension of  
176 cells. The cuvettes were then laid down horizontally for 24 hours (under  $100 \mu\text{mol photons m}^{-2}$   
177  $\text{s}^{-1}$ ) to induce the formation of the biofilm only on one face of the cuvette. After this time  
178 interval, the medium was flown at a flow rate of  $0.2 \text{ mL min}^{-1}$  (**a good compromise to avoid**  
179 **large volumes of growth medium and leakages**) and the light was continuously provided at a  
180 photon flux density of  $100 \mu\text{mol photons m}^{-2} \text{ s}^{-1}$  from the top using an Alpheus illumination  
181 system that uses a mix of blue, white and red LEDs (Alpheus LED, Montgeron, France; **see**  
182 **figure S1 for the emission spectra of the LEDs**).

183 In this study, the biofilms were grown for four days, a time necessary (based on our inoculum  
184 size) to reach a *plateau* and to avoid colonization of the biofilms on all faces of the cuvette.  
185 For each experiment, a set of 6 flow-through cells was used. Three flow cells were used over  
186 the total length of the experiment (4 days) and measured every day at the spectrophotometer,  
187 CLSM, OCT, PAM and for light attenuation while of the remaining three, one flow cell for  
188 each day was opened and the biofilm scraped for FTIR measurements. Each experiment was  
189 repeated three times over three different weeks in order to obtain independent assays.

190

### 191 *Light attenuation*

192 Photon flux density was measured using a light meter (LI-190/R; LI-COR Biosciences  
193 GmbH, Bad Homburg, Germany). Light attenuation by the biofilms was monitored by placing  
194 the flow-cells on the sensor of the light meter. Light attenuation was measured in three  
195 positions along the length of each cuvette. The attenuation of light was expressed with respect  
196 to the transmitted light measured before the inoculation of the flow cells (transmitted light<sub>(0)</sub>;  
197 measured at day 0) as follow:

198

$$199 \text{ Light attenuation}_{(i)} (\%) = [1 - (\text{transmitted light}_{(i)} / \text{transmitted light}_{(0)})] \cdot 100 \quad (1)$$

200

201 Where *i* represents the day during the growth of the biofilms.

202

### 203 *Chlorophyll a variable fluorometry (PAM)*

204 The photosynthetic efficiency of the biofilms was determined using a portable pulse  
205 amplitude modulation (PAM) fluorometer (AquaPen, AP 110-C, Photon Systems Instruments,  
206 Drasov, Czech Republic) as described in Li et al. (Li et al., 2021). Briefly, the measurements  
207 were performed by placing the face of the cuvette colonized by the biofilms in contact with



208 the blue LED (455 nm) of the instrument, the measuring light was  $0.02 \mu\text{mol m}^{-2} \text{s}^{-1}$  and  
209 saturation pulses had an intensity of  $3000 \mu\text{mol m}^{-2} \text{s}^{-1}$ . Furthermore, in order to understand if  
210 the biofilm lifestyle might interfere with the measurements, the biofilms of both microalgae  
211 were also measured after resuspension in the respective growth media ( $\text{OD}_{676}$  adjusted to 0.1  
212 in order to have optically thin samples). Before each measurement, all samples were dark-  
213 adapted for 10 minutes. Afterward, the samples were exposed to seven actinic lights (from 0  
214 to  $1000 \mu\text{mol m}^{-2} \text{s}^{-1}$ ) applied every 60s. The maximum quantum yield ( $F_v/F_m$ ) and the  
215 effective quantum yield ( $\Delta F/F'_m$ ) were calculated according to Eq. (2) and Eq. (3):

216

$$217 \quad F_v/F_m = (F_m - F_0)/F_m \quad (2)$$

$$218 \quad \Delta F/F'_m = (F'_m - F)/F'_m \quad (3)$$

219

220 where  $F_0$  and  $F_m$  are the minimum and max fluorescence determined after 10 min dark-  
221 adaptation, whereas  $F$  and  $F'_m$  are the minimum and max fluorescence during illumination.

222 The relative electron transport rate (rETR) was calculated using the Eq. (4):

223

$$224 \quad \text{rETR} = \Delta F/F'_m \times \text{PFD} \times 0.5 \quad (4)$$

225

226 Where PFD is the incident photon flux density and 0.5 is a factor assuming that two photons  
227 are required for linear electron transfer. Light curves were quantitatively compared using the  
228 parameters of maximum rate of relative ETR ( $\text{rETR}_{\text{max}}$ ),  $\alpha$  (the initial slope of the curves) and  
229  $E_k$  ( $E_k = \text{rETR}_{\text{max}}/\alpha$ ; the photon flux density at saturation) obtained by fitting the rETR vs.  
230 PFD curves with the rectangular hyperbola  $\text{rETR} = \text{rETR}_{\text{max}} (1 - e^{-\alpha \text{PFD}/\text{rETR}_{\text{max}}})$  (Ralph and  
231 Gademann, 2005).

232

233 *ATR-FTIR spectroscopy*

234 Each day, a biofilm was scrapped from one of the cuvettes. The samples were centrifuged at  
235 8000 · g for 5 minutes and the supernatant removed. After that, 1 mL of distilled water in the  
236 case of *C. vulgaris* and 1 mL of a solution of NaCl (35 g · L<sup>-1</sup>) for *C. closterium* were used to  
237 wash the biofilm suspensions. Afterward, the pellet was re-suspended in 5-10 µL of distilled  
238 water or NaCl and 1.5 µL were transferred on a 45° ZnSe flat crystal of an ATR-FTIR  
239 PerkinElmer Spectrum-two spectrometer (PerkinElmer, Waltham, USA) and the sample was  
240 dried at room temperature for 20 minutes. Spectra were acquired in the range 4000 and 400  
241 cm<sup>-1</sup> using 32 accumulations at a spectral resolution of 4 cm<sup>-1</sup>. Before each measurement, the  
242 empty crystal was measured using the same instrumental setting and used as a blank.  
243 Spectra were baselined and the ratios carbohydrates to proteins, lipids to proteins and  
244 carbohydrates to lipids were calculated as the ratios between the maximum absorption values  
245 for the spectral ranges corresponding to proteins (Amide I, νC=O; 1700–1630 cm<sup>-1</sup>), lipids  
246 (νC=O; 1750–1700 cm<sup>-1</sup>), and carbohydrates (νC–O–C, and νSi–O in diatoms; 1200–950  
247 cm<sup>-1</sup>). The band assignments were based on Sacket et al. (Sackett et al., 2013). The ratios  
248 were calculated to follow over time the changes in the macromolecular composition of the  
249 cells.

250

251 *In-vivo absorption visible spectroscopy*

252 Absorption spectra were measured using a UV-Vis spectrometer (Evolution 60S;  
253 Thermoscientific). Absorption spectra were measured in the range 400-750 nm using a  
254 spectral resolution of 1 nm. In the first days of growth each biofilm was scanned at least 8  
255 times and the spectra averaged to increase the signal to noise ratio. The absorption at 750 nm  
256 was further subtracted to all the wavelengths to remove the background. The ratio between the  
257 absorption at 435 nm and that at 676 nm (Abs<sub>435</sub> to Abs<sub>676</sub> ratio) was further calculated as an

258 index of accessory pigments to chlorophyll *a* ratio in *in vivo* microalgae spectra (Dubinsky et  
259 al., 1986; SooHoo et al., 1986).

260

### 261 *Confocal laser scanning microscopy and image analysis*

262 The biofilms were scanned using a confocal laser scanning microscope (CLSM) to obtain z-  
263 stacks of cells signal. The images were acquired using an inverted Zeiss LSM700 confocal  
264 microscope (Carl Zeiss microscopy GmbH, Jena, Germany) equipped with a LD Plan-  
265 Neofluar 20x/0.4 Korr M27 objective with a 0.4 N.A. (numerical aperture). Each image (1568  
266 x 1568 pixels; 12 bit) was 638 · 638 µm in size with a z-step of 3.9 µm and a lateral  
267 resolution of 0.41 µm. Each flow-cell was scanned in at least 6 random positions, from the  
268 inlet to the outlet, along the length of the cuvette.

269 Cells were detected by chlorophyll *a* auto-fluorescence. Chlorophyll *a* was excited at 639 nm  
270 and was detected using a long pass filter 615 nm. On the last day of growth, a biofilm  
271 cultivated in one of the cuvettes was also stained using a mix (5µL each diluted in 1 mL of  
272 respective growth media) of FITC-lectins (CON A, RCA I, SBA, PNA, DBA, WGA, UEA I;  
273 Vector Laboratories, Peterborough, UK) to visualize the matrix (i.e. the glycoconjugates) and  
274 to qualitatively compare the biofilms. This solution was later injected in a cuvette containing a  
275 biofilm that was incubated in the dark for 30 minutes before the acquisition of the images.  
276 FITC was excited using the 488 nm laser line.

277 A custom script running in Fiji (Schindelin et al., 2012) was used to extract from the z-stacks  
278 the quantitative parameters (based on the Chl*a* fluorescence) used to characterize biofilm  
279 architecture: biovolume, maximal and mean thickness and roughness (See supporting  
280 information for calculations; Tab.S1). The structural parameters were calculated according to  
281 the computations described in Heydorn et al. (Heydorn et al., 2000; see also Tab.S1) and the  
282 thresholding was performed using the Otsu algorithm (Otsu, 1979) considering the histogram

283 of the whole stack. The z-stacks were obtained over the whole length of the cuvette and the  
284 results averaged.

285

### 286 *Optical coherence tomography (OCT)*

287 The meso-structures of the biofilms were visualized using a spectral domain Optical  
288 Coherence Tomograph (OCT; Ganymede 621, Thorlabs GmbH, Lübeck, Germany) with a  
289 central light source wavelength of 900 nm. The images were acquired using a telecentric scan  
290 lens (OCT-LK3-BB) at a speed of 25kHz per A-scan and an averaging of 6 A-scan. The field  
291 of view was 4 x 4 mm (XY) and the axial depth 1 mm (Z). The lateral pixel resolution was 8  
292  $\mu\text{m}$  and the axial pixel resolution was 1.45  $\mu\text{m}$ . For all the acquisitions a refractive index of  
293 1.33 was used as the biofilms were imaged *in situ* in liquid medium (Wagner and Horn,  
294 2017). Images were analysed using the software ThorImageOCT 5.4.4 (Thorlabs, Lübeck,  
295 Germany). OCT measurements were performed only on one of the cuvettes to show the  
296 versatility of the flow cell system.

297

### 298 *Statistics*

299 Statistics was performed using GraphPad prism 5.0 (San Diego, CA, USA) and the R software  
300 (R Core Team, 2014). Before statistical analysis, the distribution of the data was investigated  
301 using the Shapiro-Wilk's test. Data were transformed (log or square root) in the case they did  
302 not followed a normal distribution ( $P < 0.05$ ). To evaluate the significance of mean differences  
303 over time, One-way and Two-way ANOVA followed by the Tukey's post-hoc test for  
304 multiple comparisons were carried out ( $ns = P \geq 0.05$ ;  $* = P < 0.05$ ;  $** = P < 0.01$ ;  $*** =$   
305  $P < 0.001$ ). The level of significance was always set at 5%. The heatmap was performed in R  
306 using the package "NMF" (Gaujoux and Seoighe, 2010). The analysis was conducted on the  
307 mean values of all experiments performed in the study and the matrix of variables was further

308 scaled using z-score scaling. Clustering of the variables was obtained using the Euclidean  
309 distance.

310

## 311 **Results and Discussion**

### 312 *Biofilm architecture is species dependent*

313 The flow cell developed in this study was used to easily cultivate microalgae biofilms and to  
314 use several optical approaches to characterize their structures and physiology (i.e. metabolic  
315 activity and biochemical composition).

316 The optical properties of the cuvettes allowed to acquire high quality images by means of  
317 CLSM and OCT (Fig.2, Fig.S2, Fig.S3). The two species were chosen since they form  
318 biofilms with different architectures (Fanesi et al., 2019; Fanesi et al., 2021; Le Norcy et al.,  
319 2019) and were therefore good experimental organisms to test the hypothesis that complex  
320 architectures may induce stronger physiological adjustments in the cells. Figure 2, Fig.S2 and  
321 Fig.S3 show indeed that biofilm structure (both cells and EPS organizations) was species-  
322 dependent, in line with previous results (Fanesi et al., 2019; Le Norcy et al., 2019) and it  
323 appeared to be homogeneous along the length of the cuvettes (Fig.S4). *C. closterium*

324 produced biofilms that were twofold thicker and that produced 2.4 times more biomass than  
325 those of *C. vulgaris* (Fig. 3a,b). Biofilms produced by *C. vulgaris* did not seem to grow much  
326 in thickness (~20µm) but seemed mostly to become denser on the substrate surface (Fig.3a,b).

327 The increase in biomass in *C. closterium* on the contrary matched an increase in thickness of  
328 the biofilms that reached up to 80 µm final thickness (Fig.2 and Fig.3a,b). These results are in  
329 agreement with previous reports about microalgae biofilms (Fanesi et al., 2019; Fanesi et al.,  
330 2021; Faÿ et al., 2010; Le Norcy et al., 2019) and are likely related to the preferential lifestyle  
331 of the two species: *C. closterium* is commonly found forming microphytobenthos  
332 communities in mudflats whereas *C. vulgaris* is generally a planktonic species. However,

333 under specific conditions, both have been reported to switch to the respective opposite  
334 lifestyle for example due to sediment resuspension for the first or contaminations and shift in  
335 light spectra for the latter (Aigner et al., 2020; Hultberg et al., 2014; Irving and Allen, 2011;  
336 Kingston, 2009).

337 The production over time of daughter cells led to a stronger light attenuation through the  
338 biofilms in both species (Fig.3d). After four days of development, *C. closterium* attenuated  
339 almost 60% of the incoming photons whereas *C. vulgaris* only 20%. Therefore, the lower  
340 biomass produced by *C. vulgaris* was likely not related to a light limitation, indeed the  
341 compensation point for *C. vulgaris* biofilms has been reported to be in the range 30-60  $\mu\text{mol}$   
342  $\text{m}^{-2} \text{s}^{-1}$  (Rincon et al., 2019). Furthermore, recently Fanesi et al. (Fanesi et al., 2021) showed  
343 that even when biofilm architecture changes, *C. vulgaris* maintains constant diffusion  
344 characteristics in its biofilm. It results that a limitation by nutrients under dynamic conditions  
345 should be excluded. On the other hand, the authors demonstrated that at low shear stress the  
346 biofilms were very loose and that cells detached more easily from the biofilm. It is therefore  
347 probable that the hydrodynamic conditions used did not allow the cells to build up strong and  
348 biomass-rich biofilms.

349

#### 350 *Biofilm architecture affects cell physiology*

351 Interestingly, the different architectural features exhibited by the biofilms of the two algal  
352 species were reflected in different physiological responses of the cells.

353 The photosynthetic performance of the cells was assessed by PAM fluorometry and the  
354 cultivation of the biofilms on one of the faces of the flow cell-cuvette allowed to perform the  
355 measurements directly *in situ*. The samples were also resuspended to test possible  
356 interferences of the biofilm lifestyle with the measurement, **in this case structural integrity of**  
357 **the biofilms was however lost**. Interestingly, the results presented in Fig.4, Fig.S5 and Tab.S2

358 and S3 show a strong dependency of the measurements on the species considered and on the  
359 thickness of their biofilms. Regardless of the time point, the thin biofilms formed by *C.*  
360 *vulgaris*, presented very similar photosynthetic responses both when measured *in situ* or in the  
361 suspended mode (Fig.4). On the other hand, in *C. closterium* a strong deviation of the rETR  
362 was observed between *in situ* and suspension measurements after two days of development  
363 (Fig.4). This response has been extensively described in the literature for microphytobenthic  
364 communities and it has been attributed to the attenuation of light as it penetrates through a  
365 biofilm and to the integration of the fluorescence response over the whole biofilm depth  
366 (Consalvey et al., 2005; Perkins et al., 2010). Thanks to the parallel measurements of  
367 structures and photosynthesis, we identified a threshold thickness of 60  $\mu\text{m}$  that would still  
368 ensure linearity of the technique with our instrument (see Fig.S5). On the base of these  
369 observations, only the results coming from the resuspension of *C. closterium* biofilms were  
370 considered for interpretation, whereas the *in situ* measurements were retained for *C. vulgaris*.  
371 As the biofilms produced by *C. closterium* developed, at day4 the photosynthetic capacity of  
372 the cells was 40% lower ( $P < 0.05$ ) with respect to that at day1 and the rETR saturated at lower  
373 PFD values ( $P < 0.05$ ; 46% lower  $E_k$  value) (Fig 4a,e). On the other hand, the photosynthetic  
374 performance of the cells of *C. vulgaris* did not appear to be negatively affected as the biofilms  
375 matured (Fig.4a). Since the thickness of *C. closterium* biofilms doubled at day4, the decrease  
376 in photosynthetic capacity could have been induced by a rate limiting resource related to the  
377 greater structural complexity of the biofilms. In accordance with Rincon et al.(Rincon et al.,  
378 2019), the maximum quantum yield ( $F_v/F_m$ ) in both species did not change over time ( $P > 0.05$ ;  
379 Fig.4g,h). The combination of a constant  $F_v/F_m$  and the decrease in  $\text{rETR}_{\text{max}}$  in *C. closterium*  
380 suggests that photosynthetic capacity could have been limited by DIC rather than nutrients  
381 such as N and P. Forster and Martin Jézéquel (Forster and Martin-Jézéquel, 2005) came to  
382 similar conclusions for diatoms biofilms grown under dynamic conditions. Furthermore, since

383 at day4 the attenuation of light by the biofilms reached 60% of the incident light, the decrease  
384 in  $rETR_{max}$  and the parallel increase in  $\alpha$  could also be indicative of an acclimation of the  
385 biofilms to lower photon flux densities (Dubinsky and Stambler, 2009; Li et al., 2021). This  
386 interpretation would also fit with the progressive decrease of the Abs<sub>435</sub> to Abs<sub>676</sub> ratio over  
387 time ( $P < 0.05$ ; Fig.5a,b) that is a typical response of cells growing at lower light intensities  
388 (Dubinsky et al., 1986; SooHoo et al., 1986). Therefore, we cannot rule out a combined effect  
389 of light and nutrients as the biofilms of *C. closterium* became more complex from a structural  
390 point of view.

391 Similarly to the photosynthetic parameters, substantial changes in the macromolecular  
392 composition of the cells only occurred in *C. closterium* (Fig.5): a decrease over time in the  
393 carbohydrates to proteins ratio ( $P < 0.05$ ; 20%) and an increase in the lipids to proteins ratio  
394 ( $P < 0.05$ ; ~40%), whereas no compositional change was exhibited by *C. vulgaris* ( $P > 0.05$ ;  
395 Fig.5). This results further strengthen the hypothesis of a possible nutrient and light co-  
396 limitation in *C. closterium*. Indeed, lower photosynthetic capacity and accumulation of  
397 storage compounds such as lipids are typical strategies already described for the  
398 phytoplankton growing under stressful/limiting conditions and of cultures entering the  
399 stationary phase (Kamalanathan et al., 2016). Although for bacterial biofilms correlations  
400 between macromolecules and structures have been described (Feng et al., 2015; Tan et al.,  
401 2018), reports about photosynthetic biofilms are scarce (Fanesi et al., 2019; Wang et al., 2021;  
402 Wijihastuti et al., 2017).

403 The heatmap summarizes the dynamics of the biofilm traits for the two species. *C. closterium*,  
404 the algae that built the greater biofilms, underwent the greater changes in terms of metabolic  
405 activity and cellular composition, as it can be seen by the more frequent changes in colors in  
406 the heatmap for most of the investigated traits (see Fig.6). On the other hand, the thinner  
407 biofilms developed by *C. vulgaris* did not induce any drastic change in cell physiology



408 (constant colors in Fig.6). Also, the clustering of structural parameters such as thickness (max  
409 and mean) and biovolume with light attenuation, photosynthesis and compositional  
410 parameters confirms that the decrease in PFD over time was probably responsible for the  
411 acclimation strategy undertaken by *C. closterium*. Changes in cell activity as a function of  
412 biofilm structural complexity have been previously reported for bacteria strains (Piculell et  
413 al., 2016; Stewart and Franklin, 2008; Sun et al., 2016; Torresi et al., 2016), but only few  
414 reports are available for photosynthetic biofilms (Stiefelmaier et al., 2020; Wang et al., 2021;  
415 Wijihastuti et al., 2017). The high physiological plasticity exhibited by benthic diatoms has  
416 long been recognized as a functional trait that allows the cells to rapidly acclimate in an  
417 extremely variable and harsh environment such as intertidal sediments (Forster and Martin-  
418 Jézéquel, 2005). Here, we suggest that such a trait might be advantageous in those species  
419 capable of building complex (i.e. thicker and with more biomass) biofilms, since it would  
420 allow the cells to promptly acclimate to the changing local conditions along biofilm  
421 maturation. In support to this, the ability of monospecific microalgae biofilms to promptly  
422 acclimate (both physiology and architecture) to changing environmental conditions (i.e. light  
423 intensity) has been recently demonstrated also by Wang et al. (Wang et al., 2021), suggesting  
424 that such a phenotypic plasticity must be taken into account also when designing biofilm-  
425 based systems for biotechnological applications.

426 Further studies would be necessary to identify the precise rate-limiting resource inducing such  
427 physiological reorganization as a function of changing biofilm architecture, for example by  
428 integrating in the experimental set-up nutrients and pH sensors. Likely a combination of light  
429 quantity and spectrum and nutrient limitation could be the principal reason (Fanesi et al.,  
430 2019; Yuan et al., 2020; Zhang et al., 2019). It must be also kept in mind that the techniques  
431 used in this study to characterize cell photosynthesis and macromolecular composition are  
432 integrating the parameters over the whole cell population. Techniques with a higher spatial

433 resolution (i.e. Imaging PAM and FTIR/Raman micro-spectroscopy) may help to discriminate  
434 the spatial distribution of cell phenotypes in photosynthetic biofilms and to properly explain  
435 acclimation strategies at a finer scale (Stewart and Franklin, 2008).

436

## 437 **Conclusions**

438 The use of UV/Vis-spectroscopic cuvettes as flow cell **allowed a screening, by means of**  
439 **optical methods, of several biofilm traits (from metabolic activity to microscopic structures)**  
440 **mostly *in situ***, allowing to comprehend the interplay between structure development during  
441 the maturation of photosynthetic biofilms and their respective changes in photosynthetic  
442 activity and macromolecular composition. We were able to show that the development of  
443 more complex biofilms, from an architectural point of view, leads to greater changes in cell  
444 activity and composition likely because of changes in local environmental conditions as the  
445 biofilms grow in thickness and biomass. **The diatom developed thicker and biomass-rich**  
446 **biofilms that attenuated more light, leading to a decrease in photosynthetic performance and a**  
447 **rearrangement of cell macromolecules. On the other hand, the thinner biofilms developed by**  
448 ***C. vulgaris* did not undergo any remarkable adjustment in their physiology.** This system could  
449 be used to screen under controlled laboratory conditions several microalgae species at the  
450 same time, the interaction of mixed communities (microalgae and bacteria) and could provide  
451 a better comprehension of such complex communities for ecological and biotechnological  
452 purposes.

453

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461

#### 462 **Author Contributions**

463 AF developed the flow cell, performed the experiments, analysed the data and wrote the  
464 article, TM and CB contributed in the realization of the experimental set-up. AF, OB, RB and  
465 FL designed the experiments. OB, RB and FL provided funding, analysed the data, supervised  
466 the project and revised the manuscript.

467

#### 468 **Data availability statement**

469 The data that support the findings of this study are available from the corresponding author  
470 upon reasonable request.

471

#### 472 **Competing interests**

473 The authors declare no competing interests.

474

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## 619 **Figure legends**

620 **Figure 1.** Schematic representation of the flow cell and example of biofilm growth. Panel (a)  
621 depicts the design of the cuvette flow cell, whereas in panel (b) an example of biofilm growth  
622 over time of *C. closterium* biofilms in the cuvettes is reported.

623

624 **Figure 2.** CLSM-topographic representation of the biofilms developed by *C. closterium* and  
625 *C. vulgaris* (a) and representative OCT B-scans of *C. closterium* biofilms over time (b). The  
626 colors in the topographic representations of the biofilms are calibrated with respect to biofilm  
627 height (in  $\mu\text{m}$ , from 0 to 100  $\mu\text{m}$ ): blue colors represent the bottom of the biofilm whereas  
628 purple colors represent the top of the biofilm (see the calibration bar). The height of the  
629 biofilms is based on the *Chla* signal, therefore it represents only the thickness of the cell

630 **biomass**. The z-stacks were obtained with a CLSM and the topography of the biofilm was  
631 computed in Fiji using the TopoJ plugin.

632

633 **Figure 3.** Evolution of structural parameters of the biofilms over time. Biovolume (a), max  
634 thickness (b) and roughness **coefficient** (c), obtained from CLSM z-stacks and light  
635 attenuation (d) as a function of time in biofilms of *C. closterium* and *C. vulgaris* grown in  
636 cuvettes flow cells. The results are reported as the mean and standard deviation of at least  
637 three independent assays.

638

639 **Figure 4.** Photosynthetic parameters obtained from *in situ* biofilms (in white) and from re-  
640 suspended biofilms (in black). The panels (a), (c), (e) and (g) refer to the photosynthetic  
641 parameters measured for the biofilms developed by *C. closterium* whereas the panels (b), (d),  
642 (f) and (h) refer to the biofilms developed by *C. vulgaris*. The results are reported as the mean  
643 and standard deviation of at least three independent assays. The statistical significance is  
644 reported with respect to day1. **See Tab.S2 and S3 for the detailed statistical results.**

645

646 **Figure 5.** Pigment signatures (a and b) and macromolecular composition (c,d,e and f) of *C.*  
647 *closterium* and *C. vulgaris* biofilms over time. The absorption ratio Abs435/Abs676 is an  
648 index of the accessory pigments to chl *a* ratio and was calculated from UV-Vis spectra  
649 whereas the macromolecular ratios were obtained from FTIR spectra. The results are reported  
650 as the mean and standard deviation of at least three independent assays. The statistical  
651 significance is reported with respect to day1.

652

653 **Figure 6.** Heatmap representing the changes in biofilm traits grouped in architecture,  
654 photosynthesis, macromolecular composition and optical properties of *C. closterium* and *C.*

655 *vulgaris* biofilms over time. Red colors in the heatmap depict higher values for a variable,  
656 whereas blue colors refer to lower values for that variable. The dendrograms cluster variables  
657 presenting similar trends over time using the euclidean distance. **The heatmap was computed**  
658 **using the mean values of the variables obtained from the experimental replicates.**

659

660

661