1 An empirical failure model to predict biofouling growth on fired bricks due to

2	microalgae					
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10	Highlights					
11	- An empirical failure model about microalgae biofouling was developed					
12	- The model takes into account the main substrate properties influencing the growth					
13	- It also considers the environmental temperature and relative humidity					
14	- The model was developed and validated on fired bricks					
15	Abstract					
16	The purpose of this study was to provide an empirical failure model predicting the microalgae growth on fired					
17	bricks surfaces. It was developed through a numerical fitting of experimental data present in literature. It					
18	considered the substrate properties related to biofouling (i.e. porosity and roughness) of different bricks under					
19	several environmental conditions (i.e. relative humidity and temperature). Results shows that the model is able					
20	to simulate the microalgae biofouling by explicitly taking into account such influencing factor. Finally, this					
21	empirical failure model is validated on a different dataset from literature and applied to time varying temperature.					
22						
23	Keywords: microalgae biofouling; fired bricks; empirical failure model; substrate properties; environmental					
24	conditions;					

25 1 Introduction

When porous building materials are exposed to environmental weathering, their physicals and chemicals properties interact with biological factors, leading to changes in both its compositional and structural characteristics [1–3]. The growth process and vegetative development of organisms have a direct consequence on the material due to the metabolic activity connected with the growth of living organisms [4]. The living species that commonly dwell on these materials are ranging from microscopical bacterial cells to higher plants and animals [5].

Biofouling on porous building materials is a colonization process usually started by photoautotrophic 32 microorganisms since they only need light, water and some inorganic components to start growing [1,2]. Among 33 these, the most recurrent groups are green microalgae and cyanobacteria, shortly named as microalgae, and they 34 usually develop in combination, especially in the European context [6-8]. Frequent maintenance and repairing 35 interventions are then required in order to limit aesthetical, chemical and physical degradation they may produce: 36 both ways, either repairing or not, could ultimately cause serious losses (economical or even cultural, if cultural 37 heritage is involved) [9,10]. In order to describe and therefore limit microalgae biofouling risk on porous building 38 materials, in recent years researchers adopted two strategies [11]: (1) determining and thus limiting, when 39 possible, the influencing factors of biofouling growth; (2) providing models that can simulate and then forecast 40 the biofouling risk. 41

Regarding the first one, literature works mainly focused on the factors that influenced the water activity: that is 42 defined as the water available to microorganisms to growth [6,10,12–17]. They highlighted that a combination 43 of environmental conditions, substrate properties and intrinsic aspects of the plumbing system of buildings (i.e. 44 leaky parts and design defects of the construction) could ensure the growth and development of microalgae. For 45 what concerns the environmental conditions, it was demonstrated that microalgae growth occurred only at 46 saturation conditions [13,18], that is when water can be found at liquid state. From an engineering standpoint, 47 however, two assumption can be done: water activity can be approximated with the relative humidity RH, as 48 49 previously demonstrated in [19] and the saturation condition safety limit can be set for RH 298% [18], even though

brick surface could not be wet, and water activity is only present by capillary condensation [20]. Moreover, it 50 was proved that temperature allows microalgae to develop between about 5°C and 40°C with an optimal growth 51 condition at about 27.5°C [18,21,22]. Out of this range, microalgae growth process is unable to start or, if already 52 started, it stops [1,2,18,23]. In this context, porosity and roughness were outlined as the main factors concerning 53 the substrate properties [13,24–27]. In fact, roughness promotes the adherence of microalgae to the substrate 54 55 while porosity is responsible for retaining water inside the material structure. Moreover, when the materials structure and geometry, in terms of porosity and roughness, is able to afford enough water activity for microalgae 56 to start their growth, the chemical composition of the substrate may play only a secondary role, favouring or 57 limiting their development [28–32]. 58

For what concern the second strategy, literature has provided a reliable model for describing microalgae growth 59 starting from experimental measures [33]. Based on the Avrami's theory, it connects the area covered by 60 biofouling over the time by denoting a first phase of latency (when microalgae stains are not still visible), 61 followed by a rapid growth, and finally a stagnation phase when the covered area reaches its maximum and 62 becomes constant over the time. Such approach was applied to several type of porous buildings materials (i.e. 63 mortars, fired bricks and stones), under different environmental conditions and biocides surface treatments, 64 confirming its capabilities [18,26,33–35]. However, it never explicitly and quantitatively accounts for the growth 65 66 influencing factors of the substrate and environmental conditions, as failure models usually do. This way, no failure models still exist in literature for microalgae growth on porous building materials, to the authors' 67 knowledge, while numerous failure models have been presented for other type of biofouling (e. g. mould, fungi, 68 actinomycetes) [19,36-43]. 69

Hence, the aim of this work is to propose a first empirical microalgae growth failure model, that is able to explicitly take into account, for the first time, the main influencing factors of substrate parameters (such as porosity and roughness) and environmental conditions (such as temperature and relative humidity), as well as their variation over the time. Fired bricks are here considered due to the availability of a large set of experimental data in literature, but the methodology can be extended to other porous building materials when enough experimental data will be available. To this aim, this work is divided into three main phases. The first phase involves the definition of: the model general requirements (Section 2.1); the variables domains (Section 2.2) and the specific model equations (Section 2.3). The fitting method is then provided (Section 2.4). Lastly, resulting equations are presented and validated and the application of the model under time varying temperature is reported (Section 3).

80 2 Materials and methods

81 2.1 General requirements

82 As stated above, the starting point of this work is the modified Avrami's model [34,35] showed in (1):

$$X(t) = \frac{A_C}{A_T} \cdot (1 - \exp^{-K(t - t_1)^n})$$
(1)

83 where the covered area by microalgae growth X(t) [-] is given as a function of time t [day]. The final covered area 84 ratio is represented by the parameter A_C/A_T which expresses the percentage of the covered area at the end of the 85 process (A_C is the maximum covered area by biofouling on a specific sample, and A_T is the total area of the same 86 sample), K [day⁻⁴] is a rate parameter determined by the least squares method using experimental measurements. 87 Lastly, the parameter t_1 represents the latency time [day] before a chromatic variation occurs on the material 88 surface and the coefficient n is the Avrami's coefficient which can be assumed equal to 4 [34].

89 The model variables are chosen according to literature findings. Porosity P [-] and roughness R [µm] are the main 90 factors characterising the substrate [6,25,26] and, their values are easily measurable and available in literature 91 (see Section 2.2). Temperature T [°C] and relative humidity RH [%] are instead selected as the main factors 92 representing environmental conditions [13,14,18].

93 In this way:

94 - since literature showed that, regardless of the temperature, *RH* determines the actual possibility for
 95 microalgae to growth, according to which growth happens only if *RH*≥98% [18], it can be considered as
 96 an on/off factor;

- 97 when $RH \ge 98\%$ and $5^{\circ}C \le T \le 40^{\circ}C$ growth can happen depending on *T*, *P* and *R*, otherwise it cannot 98 [13,18];
- 99 thus, *P*, *R* and *T* directly affect the microalgae coverage *X* through its parameters A_C/A_T , *K* and t_1 100 [18,26,34,35].

101 Inorganic compounds are here not directly considered due to their difficult measurement and their possible non-102 homogeneous distribution, but they are assumed as available. At the same time, an optimal day/night period is 103 assumed to consider the influence of the light. These come from the choice of the experimental dataset (see 104 Section 2.2). Both these assumptions can be considered as conservative standpoints.

105 Equation (2) shows the analytical translation of the previous requirements.

$$X(T, RH, P, R, t) = \Omega(RH) \cdot \frac{A_C}{A_T}(T, P, R) \cdot \left[1 - \exp^{-K(T, P, R) \cdot \left(t - t_1(T, P, R)\right)^4}\right]$$
(2)

106 where the $\Omega(RH)$ is defined as in (3) and 5°C $\leq T \leq 40$ °C.

$$\Omega(RH) = \begin{cases} 0, RH < 98\% \\ 1, RH \ge 98\% \end{cases}$$
(3)

107 Besides, two analytical requirements over the time t can be stated, as reported in (4).

$$\begin{cases} X(t) = 0, \forall t < t_1(T, P, R) \\ X(t_i) \le X(t_{i+1}), \forall t_i < t_{i+1} \end{cases}$$
(4)

The first one involves the latency time t_1 and it tries to overcome an analytical inaccuracy. In fact, the use of t_1 can lead to a miscalculation on the covered area: since the function is even, when the latency time is different from 0, the covered area at t=0 is higher than 0 with a decreasing trend between t = 0 and $t = t_1$. This means that the growth curve minimum is equal to 0 when $t=t_1$, too. This is not so correct from a physical description of microalgae growth, even if t_1 is usually very short if compared to the total growth time and the predicted biofouling coverage in this interval is rather poor. Thus, microalgae growth is set to be 0 until the latency time is reached. The second condition states that the model has to be a monotonically not decreasing function, that is, the reached covered area can be constant or it can increase, according to the environmental conditions. In fact,

116 previous researches showed that, once settled, microalgae are able to retain water inside them and therefore 117 survive i.e. dry periods [2,44].

118 2.2 The experimental dataset and domains determination

For the experimental dataset based on fired brick substrates, no novel experimental tests are performed, but a 119 very large dataset coming from a previous work [18] is used. This dataset is in fact: (1) comparable to other ones 120 of previous failure model used in literature [19,39,45,46] and (2) representative of the main influencing growing 121 factors for microalgae, such as P and R. Moreover, it considers two of the most recurrent species of microalgae 122 on building materials [6], namely Chlorella mirabilis (green microalga) and Chroococcidiopsis fissurarum 123 124 (cyanobacterium), by accounting for them an optimal day/night period equal to 14/10 h respectively[18] and an adequate level of inorganic compound, according to ASTM D5589-09 standard method [47]. 125 Table 1 summarizes the substrate properties (P and R) of the five fired bricks (SP₁, ..., SP₅), and the seven 126

127 different environmental combinations of T and RH (EC₁, ..., EC₇).

128 Table 1. Combination of the tested substrate properties (SP) and environmental conditions (EC) [18]. Three samples were tested for each substrate property (SP).

	Substrate Properties			Environmental Conditions Temperature [°C] – Relative humidity [%]							
	Porosity [-]	Roughness [µm]	EC ₁	EC_2	EC ₃	EC ₄	EC5	EC ₆	EC7		
\mathbf{SP}_1	0.19	4.50									
SP_2	0.19	5.54	T=27.5 RH=75								
SP_3	0.25	2.95		T=27.5	1=27.5 DIL-75	T=27.5	T=27.5	T=5	T=10	T=27.5°C	T=40
SP_4	0.44	6.60		KH=8/	KH=98	KH≈100	KH≈100	KH≈100	кн≈100		
SP ₅	0.44	7.60									

130

Materials SP₁, SP₃ and SP₅ are considered for the fitting process since they are comprehensive of the substrate domain, representing the minimum, maximum and intermediate values for both *P* and *R*. On the other hand, SP₂ and SP₄ are used in the post fitting process in order to validate its results. All the tested environmental conditions are taken into account in the fitting process. Hence, the dataset for the experimental fitting process is composed by 63 experimental microalgae growth curves, referring to 3 samples for 3 substrates under 7 different environmental conditions and by 42 curves for the validation step.

Common *P* and *R* values of fired bricks were also investigated [25–27,29,35,48–54] to see how the experimental data set (Table 1) is representative. This way, an application range for the empirical failure model can be provided. The review described 60 different brick porosity and 20 roughness values, respectively (Figure 1). It is worth noting that the (open) porosity and the roughness, usually considered in literature [25,27,29,35,48,54,55] as microalgae growing factors, are those determined according to the ASTM D4404-10 standard [56] and UNI EN ISO 4287:2009 standard¹ [57], respectively. We will refer to such references in the following.



Figure 1. Comparison between porosity and roughness values from literature [25–27,29,35,48–54] and the porosity and roughness domain from the selected database [18].

147 By comparing the literature review results and the experimental dataset reported in Table 1, the domain for P148 and R is set as reported in (5).

$$\begin{cases} 0.19 \le P \le 0.44 \\ 2.50 \,\mu m \le R \le 8.00 \,\mu m \end{cases}$$
(5)

149 In particular, it is worth noting that the porosity domain set for the model includes 87% samples' values, while150 the roughness domain covers 80% of samples provided by literature.

151 2.3 Experimental trend and analytical model definition

144

152 Figure 2 shows the experimental trend of the parameter A_C/A_T , K and t_1 obtained from the used dataset: the 153 parameter values refer to the specimens of the tested materials (SP₁, SP₃ and SP₅) under saturation condition (as 154 reported in EC₄, ..., EC₇), for a total of 36 experimental data for each parameter. In the between of domain, *T*

¹ Roughness values were determined according to R_a calculation.

155 predominantly influences A_C/A_T and K, determining an increasing trend from 5°C to about 27.5°C and a 156 decreasing one from about 27.5°C to 40°C. These trends hold for each P and R. Lastly, in Figure 2 (c) the latency 157 time t_1 shows a constant trend not depending on temperature, conversely, it is influenced by P and R.



Figure 2. Experimental trend of bricks parameters: (a) Ac/Ar parameter; (b) K parameter; (c) t₁ parameter. The graphs are reported according to the temperature domain. The blue scale (dark-light) indicates the increasing porosity; the increasing dimension of the spot indicates the increasing roughness value. In (b) two y-axis were used since the K parameters are significantly different: SP₁ and SP₃ refer to the left y-axis, SP₅ refers to the right y-axis.



168 are reported in (6):

$$\begin{cases} \frac{A_C}{A_T}(T, P, R) = c_{0,A}(P, R) + c_{1,A}(P, R) \cdot T + c_{2,A}(P, R) \cdot T^2 + c_{3,A}(P, R) \cdot T^3 \\ K(T, P, R) = c_{0,K}(P, R) + c_{1,K}(P, R) \cdot T + c_{2,K}(P, R) \cdot T^2 + c_{3,K}(P, R) \cdot T^3 \\ t_1(P, R) = c_{0,t}(P, R) \end{cases}$$
(6)

169 where the coefficients reported in (6) result from the fitting process (see Section 2.4).

170 Finally, the codomains of each involved parameter are reported in equation (7):

$$0 \le \frac{A_C}{A_T}(T, P, R) \le 1$$

$$K(T, P, R) \ge 0 , \forall T \in [5; 40], \forall P \in [0.19; 0.44], \forall R \in [2.50; 8.00]$$

$$t_1(P, R) \ge 0$$
(7)

171 2.4 The fitting process

172 From condition (6), a linear system of the temperature coefficient can be set as in (8).

$$\begin{cases} c_{n,A} = \alpha_{n,1,A}F_{1,A}(P,R) + \alpha_{n,2,A}F_{2,A}(P,R) + \alpha_{n,3,A}F_{3,A}(P,R) \\ c_{n,K} = \alpha_{n,1,K}F_{1,K}(P,R) + \alpha_{n,2,K}F_{2,K}(P,R) + \alpha_{n,3,K}F_{3,K}(P,R), & n = 0,...,3 \\ c_{0,t} = \alpha_{0,1,t}F_{1,t}(P,R) + \alpha_{n,2,t}F_{2,t}(P,R) + \alpha_{n,3,t}F_{3,t}(P,R) \end{cases}$$

$$\tag{8}$$

173 The F_1, \ldots, F_3 considered the effect of *P* and *R* values and they are defined in (9)

$$\begin{cases} F_{1}(P,R) \in \left\{P^{j_{1}}, R^{k_{1}}, 0\right\} \\ F_{2}(P,R) \in \left\{P^{j_{2}}, R^{k_{2}}, 0\right\}, \ j_{1}, ..., j_{3}, k_{1}, ..., k_{3} \in \mathbb{Z} \\ F_{3}(P,R) \in \left\{P^{j_{3}}, R^{k_{3}}, 0\right\} \end{cases}$$

$$(9)$$

This means that the combination of F_1, \ldots, F_3 can consider only *P* element, conversely only *R* elements, it may be resumed in a constant value (e.g. for *j* and *k* exponent resulting equal to 0) or even it can result equal to 0. This is due because the trends for both *P* and *R* were not clearly obtainable from the experimental evidences [18], and therefore determined in advanced as for temperature. 178 Hence, once set conditions (8)-(9), the fitting process is iteratively run by determining the α values and the right 179 combination of F₁,..., F₃ for the three parameters, following what is reported in (10) where F₁,..., F₃ have the 180 same degree for each surface properties SP.

$$\begin{array}{c} \alpha_{0,1} & \alpha_{0,2} & \alpha_{0,3} \\ \alpha_{1,1} & \alpha_{1,2} & \alpha_{1,3} \\ \alpha_{2,1} & \alpha_{2,2} & \alpha_{2,3} \\ \alpha_{3,1} & \alpha_{3,2} & \alpha_{3,3} \end{array} \begin{vmatrix} F_{1}(P,R) \\ F_{2}(P,R) \\ F_{3}(P,R) \end{vmatrix}_{SP1} = \begin{vmatrix} c_{0} \\ c_{1} \\ c_{2} \\ c_{3} \end{vmatrix}_{SP1}$$

$$\begin{array}{c} \alpha_{0,1} & \alpha_{0,2} & \alpha_{0,3} \\ \alpha_{1,1} & \alpha_{1,2} & \alpha_{1,3} \\ \alpha_{2,1} & \alpha_{2,2} & \alpha_{2,3} \\ \alpha_{3,1} & \alpha_{3,2} & \alpha_{3,3} \end{vmatrix} \begin{vmatrix} F_{1}(P,R) \\ F_{2}(P,R) \\ F_{3}(P,R) \end{vmatrix}_{SP3} = \begin{vmatrix} c_{0} \\ c_{1} \\ c_{2} \\ c_{3} \end{vmatrix}_{SP3}$$

$$\begin{array}{c} \alpha_{0,1} & \alpha_{0,2} & \alpha_{0,3} \\ \alpha_{1,1} & \alpha_{1,2} & \alpha_{1,3} \\ \alpha_{1,1} & \alpha_{1,2} & \alpha_{1,3} \\ \alpha_{2,1} & \alpha_{2,2} & \alpha_{2,3} \\ \alpha_{3,1} & \alpha_{3,2} & \alpha_{3,3} \end{vmatrix} \begin{vmatrix} F_{1}(P,R) \\ F_{2}(P,R) \\ F_{2}(P,R) \\ F_{3}(P,R) \end{vmatrix}_{SP5} = \begin{vmatrix} c_{0} \\ c_{1} \\ c_{2} \\ c_{3} \end{vmatrix}_{SP5}$$

$$(10)$$

181 The process stops when the following two requirements are achieved. The first requirement verifies the analytical 182 correctness of the model by determining the adjusted coefficient of determination R^2_{adj} since a multiple variable 183 regression is considered. The calculation of R^2_{adj} is shown in equation (11) and all the R^2_{adj} have to be higher than 184 0.85. Such limit was previously adopted in other models to consider the accuracy of the fitting good [58–60].

$$R_{adj}^2 = 1 - \frac{RSS}{TSS} \cdot \frac{n-1}{n-p-1} \ge 0.85$$
(11)

185 The *RSS* is the residual sum of squares between the experimental and the fitted data, *TSS* is the total sum of 186 squares of the differences between the experimental data and its mean, n is the number of observation and p is 187 the total number of explanatory variables in the model [61].

188 Subsequently, the second requirement involves the experimental correctness of the model. It is satisfied when 189 conditions reported in (12) are fulfilled.

$$\begin{cases} \min\left[\frac{A_{C}}{A_{T}}\right] \leq \frac{A_{C}}{A_{T}}(T, P, R) \leq \max\left[\frac{A_{C}}{A_{T}}\right] \\ \min\left[K_{\exp}\right] \leq K(T, P, R) \leq \max\left[K_{\exp}\right] \\ \min\left[t_{1, \exp}\right] \leq t_{1}(P, R) \leq \max\left[t_{1, \exp}\right] \end{cases}$$
(12)

After having defined all the parameters with their coefficients, the failure model is tested on SP_2 and SP_4 so as to have a first validation, following the same criteria: R^2_{adj} still has to be higher than 0.85, as analytical requirement and the experimental correctness must be verified by conditions reported in (12).

193 **3 Results**

194 3.1 The failure model for bricks

195 Condition (13) summarise the resulting α values and the combinations of F₁,..., F₃ of each parameter, by also 196 resuming condition (6) for the temperature equations.

$$\begin{cases} A_{\frac{C}{A_{T}}}(T,P,R) = \begin{vmatrix} -3.419[-] & 9.2 \cdot 10^{-2} \left[\frac{1}{\mu m} \right] & -5.7 \cdot 10^{-3} \left[\frac{1}{\mu m^{2}} \right] \\ 8.798 \cdot 10^{-1} \left[\frac{1}{cC} \right] & -3.1032 \cdot 10^{-2} \left[\frac{1}{\mu m \cdot cC} \right] & 2.16 \cdot 10^{-3} \left[\frac{1}{\mu m^{2} \cdot cC} \right] \\ -3.98 \cdot 10^{-2} \left[\frac{1}{cC^{2}} \right] & 2.8023 \cdot 10^{-3} \left[\frac{1}{\mu m \cdot cC^{2}} \right] & -2.184 \cdot 10^{-4} \left[\frac{1}{\mu m^{2} \cdot cC^{2}} \right] \\ 5 \cdot 10^{-4} \left[\frac{1}{cC^{3}} \right] & -5.21 \cdot 10^{-5} \left[\frac{1}{\mu m \cdot cC^{3}} \right] & 4.198 \cdot 10^{-6} \left[\frac{1}{\mu m^{2} \cdot cC^{3}} \right] \end{vmatrix} \begin{vmatrix} P_{2}^{2} \\ R_{2}^{2} \\ P_{1}^{2} \\ P_{1}^{2} \end{vmatrix} \end{vmatrix} \begin{vmatrix} P_{1}^{2} \\ R_{2}^{2} \\ P_{1}^{2} \\ P_{1}^{2} \end{vmatrix} \end{vmatrix} \begin{vmatrix} P_{1}^{2} \\ R_{2}^{2} \\ P_{1}^{2} \\ P_{1}^{2} \\ P_{2}^{2} \\ P_{1}^{2} \end{vmatrix} \end{vmatrix} = \begin{vmatrix} -1.018137 \cdot 10^{-6} \left[day^{-4} \right] & 2.638435 \cdot 10^{-5} \left[day^{-4} \right] & -1.109344 \cdot 10^{-3} \left[\mu m^{8} \cdot day^{-4} \right] \\ -1.018137 \cdot 10^{-6} \left[day^{-4} \right] & 2.638435 \cdot 10^{-5} \left[day^{-4} \right] & 2.729806 \cdot 10^{-4} \left[\frac{\mu m^{8} \cdot day^{-4}}{cC} \right] \\ -3.978387 \cdot 10^{-8} \left[\frac{day^{-4}}{cC^{2}} \right] & 1.173803 \cdot 10^{-6} \left[\frac{day^{-4}}{cC^{2}} \right] & -1.081282 \cdot 10^{-5} \left[\frac{\mu m^{8} \cdot day^{-4}}{cC^{3}} \right] \end{vmatrix} \begin{vmatrix} P_{1}^{2} \\ P_{2}^{3} \\ P_{1}^{2} \\ P_{2}^{3} \end{vmatrix} \end{vmatrix}$$

$$(13)$$

$$\left| t_1(P,R) = \left| 4.73 \cdot 10^{-5} \left[day \right] -2.88 \cdot 10^{-4} \left[\frac{day}{\mu m} \right] -2.66 \cdot 10^{-4} \left[\frac{day}{\mu m^2} \right] \right|_{R^2}^{P^{-8}}$$



197 Figure 3 shows that all the R^2_{adj} are higher than 0.85 for A_C/A_T , K and t_1 .

199
200
201Figure 3. Coefficient of determination R^2 of the parameter. (a) Ac/AT parameters; (b) K parameter; (c) t_1 parameter. The blue scale (dark-light)
indicates the increasing porosity the increasing dimension of the spot indicates the increasing roughness value. In (b) two y-axis were used since the
K parameters are significantly different: SP1 and SP3 refer to the left y-axis, SP5 refers to the right y-axis.

202 Lasty, both the experimental values and the fitted curves are reported in Figure 4. These last ones falls within the

203 experimental values, verifing the condition proposed in (12).





Figure 4. Comparison between the the experimental values and the fitted curves for the sufaces properties $SP_1 SP_3$ and SP_5 : (a) A_C/A_T (b) K and (c) t_1 . The blue scale (dark-light) indicates the increasing porosity; the increasing dimension of the spot indicates the increasing roughness value. In (b) two y-axis were used since the K parameters are significantly different: $SP_1 SP_3$ refer to the left y-axis, SP_5 refers to the right y-axis.

210 3.2 Failure model validation

211 The failure model is then applied on the second dataset. As shown in Figure 5, the three R^{2}_{adj} were always higher

212 than 0.85.

206



Figure 5. Coefficient of determination R^2 of the parameters. (a) A_C/A_T parameters; (b) K parameter; (c) t_1 parameter. The red scale (dark-light) indicates the increasing porosity; the increasing dimension of the spot indicates the increasing roughness value. In (b) two y-axis were used since the K parameters are significantly different: SP₂ refer to the left y-axis, SP₄ refers to the right y-axis.



218 experimental data.



219



Figure 6. Comparison between the the experimental values and the fitted curves for the sufaces properties SP_2 and SP_4 : (a) A_C/A_T (b) K and (c) t_1 . The dotted red lines indicate the minimum and maximum curve for P and R values. The red scale (dark-light) indicates the increasing porosity; the dimension of the spot (6-7) indicates the roughness value. In (b) two y-axis were used since the K parameters are significantly different: SP_2 refers to the left y-axis, SP_4 refers to the right y-axis.

As a last qualitative validation step, according to other previous model validation [39,46], the curves describing microalgae growth X(t, T, RH, P, R) are determined for the validation substrates SP₂ and SP₄ under the tested environmental condition EC₅ and EC₆ (Table 1) and overlapped to the experimental data obtained in [18]. All the curves well fit the experimental values (Figure 7).



Figure 7. Comparison of the covered area X(t, T, RH, P, R) obtained with the failure model and experimental data for SP₂, and SP₄ [18]:a) when exposed to EC₅;b) when exposed to EC₆. Lines indicate the failure model curves; points indicate the experimental data.

233 3.3 Failure model application over time-variable environmental conditions

- 234 Lastly, this paragraph shows the model application for a representative brick substrate exposed to time-variable
- 235 environmental conditions (Table 2).
- 236 Table 2. Specification for the model application.

237

aterial		Condition (C)			
Roughness [µm]	n°	Temperature [°C]	Exposure Time [day]		
2.75µm	1	14	50		
	2	7.5	50		
	3	20	50		
	4	27.5	50		
	aterial Roughness [μm] 2.75μm	aterial Roughness [μm] n° 2.75μm 1 2 3 4	aterial Conditi Roughness [µm] n° Temperature [°C] 2.75µm 1 14 2 7.5 3 20 4 27.5 27.5		

The brick properties are chosen in order to describe the most recurrent ones according to Figure 1. The assumed four conditions do not simulate a real dataset, but they allow improving the readability of the combination process. In particular, the gradient between the four temperatures values allows having four distinctive branches that significantly differ from each other and the exposure time of 50 days led the growth process for each condition be clearly recognizable. Lastly, time and the time dependent variable (*T* and *RH*) are daily discretized and kept constant during the day for sake of simplicity.

The combination of the branches over the time is made by following these 2 assumptions: (1) *P* and *R* are given and they both cannot change; (2) the coverage cannot go back and decrease, as already stated in equation (4). Hence, each involved *n*-branch of each *T*-dependent curve is joined to another n+1-curve by simply determining the time shift $t_{s,n}$ following simple steps from equation as reported in equation (14):

$$t_{s,n} = + \frac{1}{\sqrt{1 - \left(\frac{1}{K(T_{n+1})}\right) \cdot \ln\left(1 - \frac{X_n}{\frac{A_C}{A_T}(T_{n+1})}\right) - t + t_1}}$$
(14)

248 The logarithmic calculation is possible only if the reached covered area X_n is lower than the A_C/A_T (T_{n+1}), 249 otherwise the covered area is kept constant over the time. Figure 8. shows the graphical combination of such branches and the resulting curve under time variable environmental conditions. In Figure 8. (a), the *T*-curves are determined and each branch for the corresponding exposure time is selected. Since the covered area of $C_1(X_{n=1})$ is higher than the $A_C/A_T(T_{n=2})$, the latency time is not determined, and hence, for all the C_2 exposure time the covered area is maintained constant. Figure 8. (b) shows the resulting combination of the branches for C_1 , C_3 and C_4 and the constant growth curve for T=7.5°C.



Figure 8. Application of the model to time changing environmental conditions: a) combination methods; b) resulting curve for temperature variation over time. In (a) the covered area is following the colour scale green-yellow resembling microalgae biofouling effect; dots represent the selected curve; lines orange indicate the combination effect of the time shift; line grey indicates that it was not possible to determine the time shift; in (b) the colour scale yellow green is maintained for the total microalgae curve.

261 4 Conclusion

Failure models for biofouling on building materials are becoming a more and more unavoidable need: by making quantitative predictions, they can assist professionals and researchers in developing guidelines for interventions leading to a decrease in maintenance costs. Literature have already provided such models for mould and fungi growth, but it is still limited for microalgae growth. This work tries to fill this gap by presenting a novel empirical failure model for fired bricks by taking into account the main substrate and environmental parameters influencing such growth, which are porosity and roughness, as well as temperature and relative humidity. It starts from the modified Avrami's model, by determining its three main parameters from experimental results, by also improving it about some miscalculations in the range of the latency time. From the obtained results, it is evident that such model is analytically intuitive and easy to implement. From an engineering standpoint, the novel empirical model seems to be generally applicable since the tested domain of porosity and roughness covers more than 80% of the fired bricks reported in literature. Finally, the application of such model considering time variable environmental conditions is proposed too.

Future works should consider more brick type and different environmental conditions as soon as experimental data will be available. Once confirmed its correctness for bricks, the model application could be extended to other porous building materials (such as i.e. stones, plasters and mortars) prone to microalgae growth. Moreover, thanks to its ability of considering time varying environmental conditions the model could be implemented on heat and moisture simulation software, as it is already happening for other biofouling models. This will lead to the application of the failure model to a real weather dataset, even considering the water content of the substrate instead of solely relative humidity.

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285 Nomenclature

286	Experimental parame	eters by literature researches (based on modified Avrami's Theory)				
287	X	covered area by microalgae biofouling [-]				
288	A_C/A_T	parameter of final covered area ratio [-]				
289	Κ	parameter of growth rate [day ⁻⁴]				
290	t_1	parameter of latency time [day]				
291	Fitted parameters (failure model)					
292	X(t, T, RH, P, R)	covered area by microalgae biofouling [-]				
293	$A_C/A_T(T, P, R)$	parameter of final covered area ratio [-]				
294	K(T, P, R)	parameter of growth rate [day ⁻⁴]				
295	$t_1(P,R)$	parameter of latency time [day]				
296	$\Omega(RH)$	on off parameter for relative humidity [-]				
297	Variables					
298	t	time [day]				
299	Т	temperature [°C]				
300	RH	relative humidity [%]				
301	Р	total porosity [%]				
302	R	roughness [µm]				
303	Coefficients					
304	С	temperature equation coefficient				
305	α	coefficient for material properties				
306	F	element describing the effect of <i>P</i> or <i>R</i>				
307	Subscript and Superscript					
308	n	number of temperature coefficients, from 0 to 3				
309	1,2,3 numbe	er of material coefficient for both α and F values				

310	j	number of coefficient/exponents for porosity
311	k	number of coefficient/exponents for roughness
312		

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Highlights

- An empirical failure model about microalgae biofouling was developed
- The model takes into account the main substrate properties influencing the growth
- It also considers the environmental temperature and relative humidity
- The model was developed and validated on fired bricks

1 An empirical failure model to predict biofouling growth on fired bricks due to
³ 2 ⁴ ₅ microalgae
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10_{18}^{17} Highlights
 An empirical failure model about microalgae biofouling was developed An empirical failure model about microalgae biofouling was developed
12_{23}^{22} - The model takes into account the main substrate properties influencing the growth
 It also considers the environmental temperature and relative humidity It also considers the environmental temperature and relative humidity
14_{28}^{27} - The model was developed and validated on fired bricks
29 30 1531 Abstract
16_{34}^{33} The purpose of this study was to provide an empirical failure model predicting the microalgae growth on fired
17_{36}^{35} bricks surfaces. It was developed through a numerical fitting of experimental data present in literature. It
18^{38}_{39} considered the substrate properties related to biofouling (i.e. porosity and roughness) of different bricks under
19_{41}^{40} several environmental conditions (i.e. relative humidity and temperature). Results shows that the model is able
20^{42} to simulate the microalgae biofouling by explicitly taking into account such influencing factor. Finally, this 44
21_{46}^{45} empirical failure model is validated on a different dataset from literature and applied to time varying temperature.
47 2248 49
23 ⁵⁰ ₅₁ Keywords: microalgae biofouling; fired bricks; empirical failure model; substrate properties; environmental
52 245 <i>sconditions</i> ;
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Introduction 25₁1

26 ³When porous building materials are exposed to environmental weathering, their physicals and chemicals properties interact with biological factors, leading to changes in both its compositional and structural 27 28 & characteristics [1–3]. The growth process and vegetative development of organisms have a direct consequence 29^{10}_{11} on the material due to the metabolic activity connected with the growth of living organisms [4]. The living species ¹² 301 sthat commonly dwell on these materials are ranging from microscopical bacterial cells to higher plants and 31_{16}^{15} animals [5].

 32_{18}^{17} Biofouling on porous building materials is a colonization process usually started by photoautotrophic ³³²⁰microorganisms since they only need light, water and some inorganic components to start growing [1,2]. Among ²¹ $34_{2,3}^{22}$ these, the most recurrent groups are green microalgae and cyanobacteria, shortly named as microalgae, and they 3525 usually develop in combination, especially in the European context [6-8]. Frequent maintenance and repairing 36_{28}^{27} interventions are then required in order to limit aesthetical, chemical and physical degradation they may produce: 29 3730both ways, either repairing or not, could ultimately cause serious losses (economical or even cultural, if cultural 38_{33}^{32} heritage is involved) [9,10]. In order to describe and therefore limit microalgae biofouling risk on porous building ³⁴ 39₃₅materials, in recent years researchers adopted two strategies [11]: (1) determining and thus limiting, when 40_{38}^{37} possible, the influencing factors of biofouling growth; (2) providing models that can simulate and then forecast 41_{40}^{39} the biofouling risk.

42⁴²Regarding the first one, literature works mainly focused on the factors that influenced the water activity: that is 43_{45}^{44} defined as the water available to microorganisms to growth [6,10,12–17]. They highlighted that a combination 4447 of environmental conditions, substrate properties and intrinsic aspects of the plumbing system of buildings (i.e. 45_{50}^{49} leaky parts and design defects of the construction) could ensure the growth and development of microalgae. For 4652what concerns the environmental conditions, it was demonstrated that microalgae growth occurred only at 47_{55}^{54} saturation conditions [13,18], that is when water can be found at liquid state. From an engineering standpoint, 48_{57}^{56} however, two assumption can be done: water activity can be approximated with the relative humidity *RH*, as 495_{60}^{9} previously demonstrated in [19] and the saturation condition safety limit can be set for *RH* \geq 98% [18], even though

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50 ¹brick surface could not be wet, and water activity is only present by capillary condensation [20]. Moreover, it 21 ³was proved that temperature allows microalgae to develop between about 5°C and 40°C with an optimal growth 45 ⁶condition at about 27.5°C [18,21,22]. Out of this range, microalgae growth process is unable to start or, if already 53 ⁸started, it stops [1,2,18,23]. In this context, porosity and roughness were outlined as the main factors concerning 54 ¹⁰₁₁the substrate properties [13,24–27]. In fact, roughness promotes the adherence of microalgae to the substrate 55 ¹²₁₃while porosity is responsible for retaining water inside the material structure. Moreover, when the materials 56 ¹⁵₁₆structure and geometry, in terms of porosity and roughness, is able to afford enough water activity for microalgae 77₁₈to start their growth, the chemical composition of the substrate may play only a secondary role, favouring or ¹⁹ 58²Olimiting their development [28–32].

 59_{23}^{22} For what concern the second strategy, literature has provided a reliable model for describing microalgae growth 24_{24}^{24} (625 starting from experimental measures [33]. Based on the Avrami's theory, it connects the area covered by 26_{28}^{26} (biofouling over the time by denoting a first phase of latency (when microalgae stains are not still visible), 29_{29}^{20} (biofoulowed by a rapid growth, and finally a stagnation phase when the covered area reaches its maximum and 31_{32}^{32} (becomes constant over the time. Such approach was applied to several type of porous buildings materials (i.e. 34_{33}^{40} (for the bricks and stones), under different environmental conditions and biocides surface treatments, 36_{43}^{50} (for firming its capabilities [18,26,33–35]. However, it never explicitly and quantitatively accounts for the growth 36_{40}^{39} (influencing factors of the substrate and environmental conditions, as failure models usually do. This way, no 41_{34}^{674} failure models still exist in literature for microalgae growth on porous building materials, to the authors' 48_{45}^{46} (showledge, while numerous failure models have been presented for other type of biofouling (e. g. mould, fungi, 46_{46}^{46} (19,36–43].

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 70_{50}^{49} Hence, the aim of this work is to propose a first empirical microalgae growth failure model, that is able to 71_{52}^{51} explicitly take into account, for the first time, the main influencing factors of substrate parameters (such as 72_{55}^{54} porosity and roughness) and environmental conditions (such as temperature and relative humidity), as well as 73_{57}^{56} their variation over the time. Fired bricks are here considered due to the availability of a large set of experimental set of experimental in literature, but the methodology can be extended to other porous building materials when enough 60

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75 ₁experimental data will be available. To this aim, this work is divided into three main phases. The first phase 76 3involves the definition of: the model general requirements (Section 2.1); the variables domains (Section 2.2) and 77 ⁵_cthe specific model equations (Section 2.3). The fitting method is then provided (Section 2.4). Lastly, resulting 78 æquations are presented and validated and the application of the model under time varying temperature is reported 9 79 $^{10}_{11}$ (Section 3). 12 13 80142 Materia 15 16 81 $^{17}_{18}$ 2.1 Gener Materials and methods General requirements 19 19 8220As stated above, the starting point of this work is the modified Avrami's model [34,35] showed in (1): 21 22 23 24 $X(t) = \frac{A_C}{A_T} \cdot (1 - \exp^{-K(t-t_1)^n})$ (1) 83_{26}^{25} where the covered area by microalgae growth X(t) [-] is given as a function of time t [day]. The final covered area 84^{28} ratio is represented by the parameter A_C/A_T which expresses the percentage of the covered area at the end of the 29 85_{31}^{30} process (A_C is the maximum covered area by biofouling on a specific sample, and A_T is the total area of the same 863 3 sample), K [day⁻⁴] is a rate parameter determined by the least squares method using experimental measurements. 87_{36}^{35} Lastly, the parameter t_1 represents the latency time [day] before a chromatic variation occurs on the material 8838 surface and the coefficient n is the Avrami's coefficient which can be assumed equal to 4 [34]. 89_{41}^{40} The model variables are chosen according to literature findings. Porosity P [-] and roughness R [µm] are the main 904 affactors characterising the substrate [6,25,26] and, their values are easily measurable and available in literature 91⁴⁵₄₆(see Section 2.2). Temperature T [°C] and relative humidity RH [%] are instead selected as the main factors ⁴⁷ 924 grepresenting environmental conditions [13,14,18]. 49 93_{51}^{50} In this way: 94_{53}^{52} - since since literature showed that, regardless of the temperature, RH determines the actual possibility for 54 9**5**55 microalgae to growth, according to which growth happens only if $RH \ge 98\%$ [18], it can be considered as 56 96⁵⁷ 58 an on/off factor; 59 60 61 62 4 63 64 65

- 97 1 when $RH \ge 98\%$ and 5°C $\le T \le 40$ °C growth can happen depending on *T*, *P* and *R*, otherwise it cannot 98 ³ [13,18];
- 99 $\frac{5}{6}$ thus, *P*, *R* and *T* directly affect the microalgae coverage *X* through its parameters A_C/A_T , *K* and t_1 100 8 [18,26,34,35].
- 101_{11}^{10} Inorganic compounds are here not directly considered due to their difficult measurement and their possible non-12 102_1 shomogeneous distribution, but they are assumed as available. At the same time, an optimal day/night period is 14 103_1_5 assumed to consider the influence of the light. These come from the choice of the experimental dataset (see 104_1_8 Section 2.2). Both these assumptions can be considered as conservative standpoints.
- 105² (Equation (2) shows the analytical translation of the previous requirements.
 - $X(T, RH, P, R, t) = \Omega(RH) \cdot \frac{A_C}{A_T}(T, P, R) \cdot \left[1 \exp^{-K(T, P, R) \cdot (t t_1(T, P, R))^4}\right]$ (2)
- 10626where the $\Omega(RH)$ is defined as in (3) and 5°C $\leq T \leq 40$ °C.

$$\Omega(RH) = \begin{cases} 0, RH < 98\% \\ 1, RH \ge 98\% \end{cases}$$
(3)

10732Besides, two analytical requirements over the time t can be stated, as reported in (4).

- $\begin{cases} X(t) = 0, \forall t < t_1(T, P, R) \\ X(t_i) \le X(t_{i+1}), \forall t_i < t_{i+1} \end{cases}$ (4)
- 108₃8The first one involves the latency time t_1 and it tries to overcome an analytical inaccuracy. In fact, the use of t_1 39 109⁴⁰can lead to a miscalculation on the covered area: since the function is even, when the latency time is different 41 104 42 1104 3from 0, the covered area at t=0 is higher than 0 with a decreasing trend between t = 0 and $t = t_1$. This means that 44 11145the growth curve minimum is equal to 0 when $t=t_1$, too. This is not so correct from a physical description of 46 11248 microalgae growth, even if t_1 is usually very short if compared to the total growth time and the predicted 49 1135 obiofouling coverage in this interval is rather poor. Thus, microalgae growth is set to be 0 until the latency time is 51 114⁵2 reached. The second condition states that the model has to be a monotonically not decreasing function, that is, 54 1155 the reached covered area can be constant or it can increase, according to the environmental conditions. In fact, 56
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- 116 previous researches showed that, once settled, microalgae are able to retain water inside them and therefore 117 3survive i.e. dry periods [2,44].

118⁶₇2.2 The experimental dataset and domains determination

119 For the experimental dataset based on fired brick substrates, no novel experimental tests are performed, but a $120_{1,2}^{11}$ very large dataset coming from a previous work [18] is used. This dataset is in fact: (1) comparable to other ones 121140f previous failure model used in literature [19,39,45,46] and (2) representative of the main influencing growing 122_{17}^{16} factors for microalgae, such as P and R. Moreover, it considers two of the most recurrent species of microalgae ¹⁸ 123₁ son building materials [6], namely *Chlorella mirabilis* (green microalga) and *Chroococcidiopsis fissurarum* 124^{21} (cyanobacterium), by accounting for them an optimal day/night period equal to 14/10 h respectively[18] and an 125_{24}^{23} adequate level of inorganic compound, according to ASTM D5589-09 standard method [47].

126² Table 1 summarizes the substrate properties (P and R) of the five fired bricks (SP₁, ..., SP₅), and the seven 127_{29}^{28} different environmental combinations of *T* and *RH* (EC₁, ..., EC₇).

 128_{31} Table 1. Combination of the tested substrate properties (SP) and environmental conditions (EC) [18]. Three samples were tested for each substrate 129_{32} property (SP).

34 Substrate Properties			Environmental Conditions						
		Temperature [°C] – Relative humidity [%]							
Porosity [-]	Roughness [µm]	EC_1	EC_2	EC ₃	EC_4	EC ₅	EC ₆	EC7	
0.19	4.50								
0.19	5.54					T ()		— 10	
0.25	2.95	T=27.5	T=27.5	T=27.5	T=5	T=10 DU~100	T=27.5°C	T=40 DU~100	
0.44	6.60	КП=/3	КП=0/	КП=98	КП~100	КП~100	КП~100	КП~100	
0.44	7.60								
	Substrate Porosity [-] 0.19 0.19 0.25 0.44 0.44	Porosity [-] Roughness [µm] 0.19 4.50 0.19 5.54 0.25 2.95 0.44 6.60 0.44 7.60	Porosity [-] Roughness [µm] EC1 0.19 4.50 T=27.5 0.25 2.95 RH=75 0.44 6.60 T=27.5	Substrate Properties Porosity [-] Roughness [μm] EC1 EC2 0.19 4.50	Substrate Properties Envi Porosity [-] Roughness [µm] EC1 EC2 EC3 0.19 4.50	Environmental Control Substrate Properties Environmental Control Porosity [-] Roughness [μ m] EC1 EC2 EC3 EC4 0.19 4.50 7 <td< td=""><td>Substrate Properties Environmental Conditions Porosity [-] Roughness [μm] EC1 EC2 EC3 EC4 EC5 0.19 4.50 75.54</td><td>Substrate Properties Environmental Conditions Temperature [°C] – Relative humidity [%] Porosity [-] Roughness [μm] EC1 EC2 EC3 EC4 EC5 EC6 0.19 4.50 754 757.5</td></td<>	Substrate Properties Environmental Conditions Porosity [-] Roughness [μ m] EC1 EC2 EC3 EC4 EC5 0.19 4.50 75.54	Substrate Properties Environmental Conditions Temperature [°C] – Relative humidity [%] Porosity [-] Roughness [μ m] EC1 EC2 EC3 EC4 EC5 EC6 0.19 4.50 754 757.5	

13145Materials SP1, SP3 and SP5 are considered for the fitting process since they are comprehensive of the substrate

- 135_{55}^{54} by 63 experimental microalgae growth curves, referring to 3 samples for 3 substrates under 7 different
- 1365 7 environmental conditions and by 42 curves for the validation step.
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 $¹³²_{48}^{47}$ domain, representing the minimum, maximum and intermediate values for both *P* and *R*. On the other hand, SP₂ $^{49}_{133_{50}}$ and SP₄ are used in the post fitting process in order to validate its results. All the tested environmental conditions 134^{52}_{53} are taken into account in the fitting process. Hence, the dataset for the experimental fitting process is composed

138 ₁Common P and R values of fired bricks were also investigated [25-27,29,35,48-54] to see how the experimental 139 ³data set (Table 1) is representative. This way, an application range for the empirical failure model can be provided. 140 The review described 60 different brick porosity and 20 roughness values, respectively (Figure 1). It is worth enoting that the (open) porosity and the roughness, usually considered in literature [25,27,29,35,48,54,55] as 141 142^{10}_{11} microalgae growing factors, are those determined according to the ASTM D4404-10 standard [56] and UNI EN 1431 JSO 4287:2009 standard¹ [57], respectively. We will refer to such references in the following.



145³¹ Figure 1. Comparison between porosity and roughness values from literature [25–27,29,35,48–54] and the porosity and roughness domain from the 14632 selected database [18]. 33

147³⁴By comparing the literature review results and the experimental dataset reported in Table 1, the domain for P

 148_{37}^{36} and *R* is set as reported in (5).

$$\begin{cases} 0.19 \le P \le 0.44 \\ 2.50 \,\mu m \le R \le 8.00 \,\mu m \end{cases}$$
(5)

 149_{43}^{42} In particular, it is worth noting that the porosity domain set for the model includes 87% samples' values, while 1504 the roughness domain covers 80% of samples provided by literature.

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151482.3 Experimental trend and analytical model definition

1525 Figure 2 shows the experimental trend of the parameter A_C/A_T , K and t_1 obtained from the used dataset: the 153^{53}_{54} parameter values refer to the specimens of the tested materials (SP₁, SP₃ and SP₅) under saturation condition (as 154_{56}^{55} reported in EC₄, ..., EC₇), for a total of 36 experimental data for each parameter. In the between of domain, T 57

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⁵⁹ Roughness values were determined according to R_a calculation. 60

155 predominantly influences A_C/A_T and K, determining an increasing trend from 5°C to about 27.5°C and a 2 156 3 decreasing one from about 27.5°C to 40°C. These trends hold for each P and R. Lastly, in Figure 2 (c) the latency 4 157 $\frac{5}{6}$ time t_1 shows a constant trend not depending on temperature, conversely, it is influenced by P and R.



161¹¹₄₅ Figure 2. Experimental trend of bricks parameters: (a) A_{C}/A_{T} parameter; (b) K parameter; (c) t_{1} parameter. The graphs are reported according to the temperature domain. The blue scale (dark-light) indicates the increasing porosity; the increasing dimension of the spot indicates the increasing froughness value. In (b) two y-axis were used since the K parameters are significantly different: SP₁ and SP₃ refer to the left y-axis, SP₅ refers to the right y-axis.

 165_{50}^{49} In this way, aiming at determining the simplest possible model, having only 4 different temperature values, a 3^{rd}

16652 degree polynomial is set in order to describe A_C/A_T and K as functions of T, having its coefficients depending on 53

167⁵ ⁴*P*</sup> and *R*. For the t_1 parameter, a constant coefficient depending only on *P* and *R* is set. The above observations

 168_{57} are reported in (6):

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$$\begin{cases} \frac{A_{C}}{A_{T}}(T,P,R) = c_{0,A}(P,R) + c_{1,A}(P,R) \cdot T + c_{2,A}(P,R) \cdot T^{2} + c_{3,A}(P,R) \cdot T^{3} \\ K(T,P,R) = c_{0,K}(P,R) + c_{1,K}(P,R) \cdot T + c_{2,K}(P,R) \cdot T^{2} + c_{3,K}(P,R) \cdot T^{3} \\ t_{1}(P,R) = c_{0,t}(P,R) \end{cases}$$
(6)

16911 where the coefficients reported in (6) result from the fitting process (see Section 2.4).

 170_{14}^{13} Finally, the codomains of each involved parameter are reported in equation (7):

$$\begin{cases}
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\end{cases}
\begin{cases}
0 \le \frac{A_C}{A_T}(T, P, R) \le 1 \\
K(T, P, R) \ge 0 \\
t_1(P, R) \ge 0
\end{cases}, \forall T \in [5; 40], \forall P \in [0.19; 0.44], \forall R \in [2.50; 8.00] \\
t_1(P, R) \ge 0
\end{cases}$$
(7)

171272.4 The fitting process

 172_{30}^{29} From condition (6), a linear system of the temperature coefficient can be set as in (8).

$$\begin{cases} c_{n,A} = \alpha_{n,1,A}F_{1,A}(P,R) + \alpha_{n,2,A}F_{2,A}(P,R) + \alpha_{n,3,A}F_{3,A}(P,R) \\ c_{n,K} = \alpha_{n,1,K}F_{1,K}(P,R) + \alpha_{n,2,K}F_{2,K}(P,R) + \alpha_{n,3,K}F_{3,K}(P,R), \quad n = 0,...,3 \\ c_{0,t} = \alpha_{0,1,t}F_{1,t}(P,R) + \alpha_{n,2,t}F_{2,t}(P,R) + \alpha_{n,3,t}F_{3,t}(P,R) \\ 173^{38} \text{The F}_{1,...,} \text{ F}_{3} \text{ considered the effect of } P \text{ and } R \text{ values and they are defined in (9)} \\ \begin{cases} F_{1}(P,R) \in \left\{P^{j_{1}}, R^{k_{1}}, 0\right\} \\ F_{2}(P,R) \in \left\{P^{j_{2}}, R^{k_{2}}, 0\right\}, \quad j_{1},..., j_{3}, k_{1},..., k_{3} \in \mathbb{Z} \end{cases}$$
(9)

 $\left| F_{3}(P,R) \in \left\{ P^{j_{3}}, R^{k_{3}}, 0 \right\} \right|$ $^{48}_{49}$ This means that the combination of F₁,..., F₃ can consider only *P* element, conversely only *R* elements, it may be 175⁵ resumed in a constant value (e.g. for j and k exponent resulting equal to 0) or even it can result equal to 0. This is 176_{54}^{53} due because the trends for both *P* and *R* were not clearly obtainable from the experimental evidences [18], and

17756therefore determined in advanced as for temperature.

178 ₁Hence, once set conditions (8)-(9), the fitting process is iteratively run by determining the α values and the right 179 3 combination of F_1, \ldots, F_3 for the three parameters, following what is reported in (10) where F_1, \ldots, F_3 have the 180^{5}_{6} same degree for each surface properties SP.

$$\begin{cases}
\begin{vmatrix}
\alpha_{0,1} & \alpha_{0,2} & \alpha_{0,3} \\
\alpha_{1,1} & \alpha_{1,2} & \alpha_{1,3} \\
\alpha_{2,1} & \alpha_{2,2} & \alpha_{2,3} \\
\alpha_{3,1} & \alpha_{3,2} & \alpha_{3,3}
\end{vmatrix}
\begin{bmatrix}
F_{1}(P,R) \\
F_{2}(P,R) \\
F_{3}(P,R)
\end{bmatrix}_{SP1} = \begin{vmatrix}
c_{0} \\
c_{1} \\
c_{2} \\
c_{3}
\end{bmatrix}_{SP1}$$

$$\begin{vmatrix}
\alpha_{0,1} & \alpha_{0,2} & \alpha_{0,3} \\
\alpha_{1,1} & \alpha_{1,2} & \alpha_{1,3} \\
\alpha_{2,1} & \alpha_{2,2} & \alpha_{2,3}
\end{vmatrix}
\begin{bmatrix}
F_{1}(P,R) \\
F_{2}(P,R) \\
F_{3}(P,R)
\end{bmatrix}_{SP3} = \begin{vmatrix}
c_{0} \\
c_{1} \\
c_{2} \\
c_{3}
\end{bmatrix}_{SP3}$$

$$\begin{vmatrix}
\alpha_{0,1} & \alpha_{0,2} & \alpha_{0,3} \\
\alpha_{3,1} & \alpha_{3,2} & \alpha_{3,3}
\end{vmatrix}
\begin{bmatrix}
F_{1}(P,R) \\
F_{2}(P,R) \\
F_{3}(P,R)
\end{bmatrix}_{SP3} = \begin{vmatrix}
c_{0} \\
c_{1} \\
c_{2} \\
c_{3}
\end{bmatrix}_{SP3}$$

$$\begin{vmatrix}
\alpha_{0,1} & \alpha_{0,2} & \alpha_{0,3} \\
\alpha_{1,1} & \alpha_{1,2} & \alpha_{1,3} \\
\alpha_{2,1} & \alpha_{2,2} & \alpha_{2,3}
\end{vmatrix}
\begin{bmatrix}
F_{1}(P,R) \\
F_{2}(P,R) \\
F_{3}(P,R)
\end{bmatrix}_{SP5} = \begin{vmatrix}
c_{0} \\
c_{1} \\
c_{2} \\
c_{3}
\end{bmatrix}_{SP5}$$

$$(10)$$

 181_{32}^{31} The process stops when the following two requirements are achieved. The first requirement verifies the analytical 18234 correctness of the model by determining the adjusted coefficient of determination R^{2}_{adj} since a multiple variable 183_{37}^{36} regression is considered. The calculation of R^{2}_{adj} is shown in equation (11) and all the R^{2}_{adj} have to be higher than 184390.85. Such limit was previously adopted in other models to consider the accuracy of the fitting good [58–60]. 40

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$$R_{adj}^2 = 1 - \frac{RSS}{TSS} \cdot \frac{n-1}{n-p-1} \ge 0.85$$
(11)

- $^{45}_{18546}$ The RSS is the residual sum of squares between the experimental and the fitted data, TSS is the total sum of 186_{49}^{48} squares of the differences between the experimental data and its mean, *n* is the number of observation and *p* is 187_{51}^{50} the total number of explanatory variables in the model [61].

188⁵ ³Subsequently, the second requirement involves the experimental correctness of the model. It is satisfied when 54 189_{56}^{55} conditions reported in (12) are fulfilled.

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$$\begin{aligned} & \left| \min \left[\frac{A_{C}}{A_{T} \exp} \right] \leq \frac{A_{C}}{A_{T}} (T, P, R) \leq \max \left[\frac{A_{C}}{A_{T} \exp} \right] \\ & \min \left[k_{\exp} \right] \leq K(T, P, R) \leq \max \left[k_{\exp} \right] \end{aligned} \right|$$

$$\begin{aligned} & \left| \min \left[k_{\exp} \right] \leq t_{1}(P, R) \leq \max \left[t_{1,\exp} \right] \end{aligned} \right|$$

$$\begin{aligned} & \left| \min \left[t_{1,\exp} \right] \leq t_{1}(P, R) \leq \max \left[t_{1,\exp} \right] \end{aligned} \right|$$

$$\begin{aligned} & \left| \min \left[t_{1,\exp} \right] \leq t_{1}(P, R) \leq \max \left[t_{1,\exp} \right] \end{aligned} \right|$$

$$\begin{aligned} & \left| \min \left[t_{1,\exp} \right] \leq t_{1}(P, R) \leq \max \left[t_{1,\exp} \right] \end{aligned} \right|$$

$$\begin{aligned} & \left| \min \left[t_{1,\exp} \right] \leq t_{1}(P, R) \leq \max \left[t_{1,\exp} \right] \end{aligned} \right|$$

$$\begin{aligned} & \left| \min \left[t_{1,\exp} \right] \leq t_{1}(P, R) \leq \max \left[t_{1,\exp} \right] \end{aligned} \right|$$

$$\begin{aligned} & \left| \min \left[t_{1,\exp} \right] \leq t_{1}(P, R) \leq \max \left[t_{1,\exp} \right] \end{aligned} \right|$$

$$\begin{aligned} & \left| \min \left[t_{1,\exp} \right] \leq t_{1}(P, R) \leq \max \left[t_{1,\exp} \right] \end{aligned} \right|$$

$$\begin{aligned} & \left| \min \left[t_{1,\exp} \right] \leq t_{1}(P, R) \leq \max \left[t_{1,\exp} \right] \end{aligned} \right|$$

$$\begin{aligned} & \left| \min \left[t_{1,\exp} \right] \leq t_{1}(P, R) \leq \max \left[t_{1,\exp} \right] \end{aligned} \right|$$

$$\begin{aligned} & \left| \min \left[t_{1,\exp} \right] \leq t_{1}(P, R) \leq \max \left[t_{1,\exp} \right] \end{aligned} \right|$$

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$$\begin{aligned} & \left| \min \left[t_{1,\exp} \right] \leq t_{1}(P, R) \leq \max \left[t_{1,\exp} \right] \end{aligned} \right|$$

$$\begin{aligned} & \left| \min \left[t_{1,\exp} \right] \leq t_{1}(P, R) \leq \max \left[t_{1,\exp} \right] \end{aligned} \right|$$

$$\begin{aligned} & \left| \min \left[t_{1,\exp} \right] \leq t_{1}(P, R) \leq \max \left[t_{1,\exp} \right] \end{aligned} \right|$$

$$\begin{aligned} & \left| \min \left[t_{1,\exp} \right] \leq t_{1}(P, R) \leq \max \left[t_{1,\exp} \right] \end{aligned} \right|$$

$$\end{aligned}$$

$$\begin{aligned} & \left| \min \left[t_{1,\exp} \right] \leq t_{1}(P, R) \leq \max \left[t_{1,\exp} \right] \end{aligned} \right|$$

$$\end{aligned}$$

$$\end{aligned}$$

$$\end{aligned}$$

$$\end{aligned}$$

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$$\begin{cases} A_{C} (T,P,R) = \begin{vmatrix} -3.419[-] & 9.2 \cdot 10^{-2} \left[\frac{1}{\mu m} \right] & -5.7 \cdot 10^{-3} \left[\frac{1}{\mu m^{2}} \right] \\ 8.798 \cdot 10^{-1} \left[\frac{1}{\circ C} \right] & -3.1032 \cdot 10^{-2} \left[\frac{1}{\mu m} \cdot \circ C \right] & 2.16 \cdot 10^{-3} \left[\frac{1}{\mu m^{2}} \cdot \circ C \right] \\ -3.98 \cdot 10^{-2} \left[\frac{1}{\circ C^{2}} \right] & 2.8023 \cdot 10^{-3} \left[\frac{1}{\mu m} \cdot \circ C^{2} \right] & -2.184 \cdot 10^{-4} \left[\frac{1}{\mu m^{2}} \cdot \circ C^{2} \right] \\ 5 \cdot 10^{-4} \left[\frac{1}{\circ C^{3}} \right] & -5.21 \cdot 10^{-5} \left[\frac{1}{\mu m} \cdot \circ C^{3} \right] & 4.198 \cdot 10^{-6} \left[\frac{1}{\mu m^{2}} \cdot \circ C^{3} \right] \end{vmatrix} \begin{vmatrix} P_{R}^{2} \\ P_{R}^{2} \\ P_{R}^{2} \end{vmatrix} \begin{vmatrix} P_{R}^{2} \\ P_{R}^{2} \end{vmatrix} \begin{vmatrix} P_{R}^{2} \\ P_{R}^{2} \\ P_{R}^{2} \end{vmatrix} \begin{vmatrix} P_{R}^{2} \\ P_{R}^{2} \end{vmatrix} \begin{vmatrix} P_{R}^{2} \\ P_{R}^{2} \\ P_{R}^{2} \end{vmatrix} \end{vmatrix} \begin{vmatrix} P_{R}^{2} \\ P_{R}^{2} \end{vmatrix} \begin{vmatrix} P_{R}^{2} \\ P_{R}^{2} \end{vmatrix} \begin{vmatrix} P_{R}^{2} \\ P_{R}^{2} \end{vmatrix} \end{vmatrix} \end{vmatrix}$$

$$\begin{vmatrix} t_1(P,R) = \left| 4.73 \cdot 10^{-5} \left[day \right] & -2.88 \cdot 10^{-4} \left[\frac{day}{\mu m} \right] & -2.66 \cdot 10^{-4} \left[\frac{day}{\mu m^2} \right] \end{vmatrix} \begin{vmatrix} P^{-8} \\ R \\ R^2 \end{vmatrix}$$



197 ₁Figure 3 shows that all the R^2_{adj} are higher than 0.85 for A_C/A_T , K and t_1 .





 221^{23}_{24} 222^{25}_{24} Figure 6. Comparison between the the experimental values and the fitted curves for the sufaces properties SP₂ and SP₄: (a) *Ac/AT* (b) *K* and (c) *t₁*. $222^{25}_{223^{26}_{224^{27}_{24}_{27}_{27$

 226_{31}^{30} As a last qualitative validation step, according to other previous model validation [39,46], the curves describing 227_{33}^{32} microalgae growth *X*(*t*, *T*, *RH*, *P*, *R*) are determined for the validation substrates SP₂ and SP₄ under the tested 228_{35}^{35} environmental condition EC₅ and EC₆ (Table 1) and overlapped to the experimental data obtained in [18]. All the







- 234 Lastly, this paragraph shows the model application for a representative brick substrate exposed to time-variable
- environmental conditions (Table 2). 235

236 gTable 2. Specification for the model application.

9 10	M	laterial		Condition (C)			
11 12 13	Porosity [-]	Roughness [µm]	n°	Temperature [°C]	Exposure Time [day]		
14	0.19	2.75µm	1	14	50		
15							
16			2	7.5	50		
17				• •	- 0		
18			3	20	50		
19					-		
20			4	27.5	50		
237 ²¹							

238²³The brick properties are chosen in order to describe the most recurrent ones according to Figure 1. The assumed 239_{26}^{25} four conditions do not simulate a real dataset, but they allow improving the readability of the combination process. 240²⁸In particular, the gradient between the four temperatures values allows having four distinctive branches that 241_{31}^{30} significantly differ from each other and the exposure time of 50 days led the growth process for each condition 2423 3be clearly recognizable. Lastly, time and the time dependent variable (T and RH) are daily discretized and kept 243_{36}^{35} constant during the day for sake of simplicity.

24438The combination of the branches over the time is made by following these 2 assumptions: (1) P and R are given 245_{41}^{40} and they both cannot change; (2) the coverage cannot go back and decrease, as already stated in equation (4). 24643Hence, each involved *n*-branch of each *T*-dependent curve is joined to another n+1-curve by simply determining 247⁴⁵ the time shift $t_{s,n}$ following simple steps from equation as reported in equation (14):

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53 248_{55}^{54} The logarithmic calculation is possible only if the reached covered area X_n is lower than the A_C/A_T (T_{n+1}),

 $t_{s,n} = + \frac{1}{\sqrt{-\left(\frac{1}{K(T_{n+1})}\right)}} \cdot \ln\left(1 - \frac{X_n}{\frac{A_C}{A_T}(T_{n+1})}\right) - t + t_1$

2495 70 therwise the covered area is kept constant over the time.

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(14)

250 Figure 8. shows the graphical combination of such branches and the resulting curve under time variable 251 ³environmental conditions. In Figure 8. (a), the *T*-curves are determined and each branch for the corresponding ² exposure time is selected. Since the covered area of $C_1(X_{n=1})$ is higher than the $A_C/A_T(T_{n=2})$, the latency time is 253 shot determined, and hence, for all the C₂ exposure time the covered area is maintained constant. Figure 8. (b) 254^{10}_{11} shows the resulting combination of the branches for C₁, C₃ and C₄ and the constant growth curve for T=7.5°C. 0.8 X(t, T) [-] X(t, T) [-] 9.0 (-] 0.5 0.2 27.5 20 12.5 255²⁴ 255²⁵ Temperature [°C] Time [day] Time [day] a) T=27.5°C 1.0T=20°C T=14°C 0.8 T=7.5°C [emperature [°C] X(*t*,*T*,*RH*)[-] -15 0.2 0.0 -30 Time [day] b)

 257^{43} Figure 8. Application of the model to time changing environmental conditions: a) combination methods; b) resulting curve for temperature variation 258^{44} over time. In (a) the covered area is following the colour scale green-yellow resembling microalgae biofouling effect; dots represent the selected 25945 curve; lines orange indicate the combination effect of the time shift; line grey indicates that it was not possible to determine the time shift; in (b) the colour scale yellow green is maintained for the total microalgae curve.

261484 Conclusion

 262_{51}^{50} Failure models for biofouling on building materials are becoming a more and more unavoidable need: by making 263_{53}^{52} aquantitative predictions, they can assist professionals and researchers in developing guidelines for interventions 264_{51}^{50} leading to a degrees in maintenance costs. Literature have already provided such models for mould and fungi

264⁵⁵₅₆₅₆leading to a decrease in maintenance costs. Literature have already provided such models for mould and fungi 57

265₅₈ growth, but it is still limited for microalgae growth. This work tries to fill this gap by presenting a novel empirical 59

266 1 failure model for fired bricks by taking into account the main substrate and environmental parameters influencing 267 ³such growth, which are porosity and roughness, as well as temperature and relative humidity. It starts from the 268 ² modified Avrami's model, by determining its three main parameters from experimental results, by also improving 269 8it about some miscalculations in the range of the latency time. From the obtained results, it is evident that such $270_{1,1}^{1,0}$ model is analytically intuitive and easy to implement. From an engineering standpoint, the novel empirical model 2711 seems to be generally applicable since the tested domain of porosity and roughness covers more than 80% of the 272_{16}^{15} fired bricks reported in literature. Finally, the application of such model considering time variable environmental $273_{1.8}^{17}$ conditions is proposed too. 274²⁰Future works should consider more brick type and different environmental conditions as soon as experimental 275_{23}^{22} data will be available. Once confirmed its correctness for bricks, the model application could be extended to other

27625 porous building materials (such as i.e. stones, plasters and mortars) prone to microalgae growth. Moreover, thanks 277_{28}^{27} to its ability of considering time varying environmental conditions the model could be implemented on heat and 27830moisture simulation software, as it is already happening for other biofouling models. This will lead to the 279_{33}^{32} application of the failure model to a real weather dataset, even considering the water content of the substrate $^{34}_{280_35}$ instead of solely relative humidity.

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286	² ³ Experimental parame	ters by literature researches (based on modified Avrami's Theory)
287	5 6X	covered area by microalgae biofouling [-]
288	7 8A _C /A _T 9	parameter of final covered area ratio [-]
289_{1}^{1}	${}^{0}_{1}K$	parameter of growth rate [day ⁻⁴]
2901 1	2 3t ₁ 4	parameter of latency time [day]
291 <mark>1</mark>	⁵ <i>Fitted parameters (fa</i>	ilure model)
1 292 1	7 8 <i>X</i> (<i>t</i> , <i>T</i> , <i>RH</i> , <i>P</i> , <i>R</i>) 9	covered area by microalgae biofouling [-]
293 ²	${}^{0}A_{C}/A_{T}\left(T,P,R\right)$	parameter of final covered area ratio [-]
2942	$^{2}_{3K}(T, P, R)$	parameter of growth rate [day ⁻⁴]
295 ²	$5t_1(P, R)$	parameter of latency time [day]
2962	$^{7}_{8}\Omega(RH)$	on off parameter for relative humidity [-]
2973 3	9 0Variables 1	
298 ³	2 3 ^t	time [day]
3 2993 2	4 5T 6	temperature [°C]
300 ³	⁷ <i>RH</i>	relative humidity [%]
3014 4	9 0 P 1	total porosity [%]
302 ⁴	$\frac{2^{2}R}{3}$	roughness [µm]
303 ₄	4 5Coefficients	
3044 4	8 7 <u>c</u> 8	temperature equation coefficient
305 ⁴	9 0 ^α	coefficient for material properties
3065 5	2F 3	element describing the effect of <i>P</i> or <i>R</i>
307 ⁵	⁴ Subscript and Superso	cript
3085 5	6 7n 8	number of temperature coefficients, from 0 to 3
309 ⁵	9 _{1,2,3} number	r of material coefficient for both α and F values
d 6	2	
ь б К	5 4 5	

310 <u>1</u> j	number of coefficient/exponents for porosity
$311\begin{vmatrix} 3\\ 3\\ 4\end{vmatrix}$	number of coefficient/exponents for roughness
312 6	
7 8	
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Declaration of interests

 \boxtimes The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

□The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Authors Statement

Quagliarini: Supervision, Validation, Writing - Review & Editing. Gregorini: Methodology, Formal Analysis, Writing – Original Draft. D'Orazio: Supervision, Conceptualization.