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Research Article

Bioreceptive Building Facades: Codesigning with Nature

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Abstract

Although interactions between microorganisms and building materials have long been studied in the context of biodeterioration, actively enhancing the bioreceptivity of materials for microbially greened facades is a relatively new field. In our research we explore how concrete cladding used on building facades can be engineered to support the natural development of photosynthetic biofilms. Various factors related to concrete composition and surface texture were evaluated through a multi-phase testing process. A model dual-species biofilm composed of an alga and a microcolonial fungus was developed and successfully integrated into the experimental setup. The algal's growth and vitality were assessed using Pulse-Amplitude Modulation (PAM) fluorometry. Findings underscore the importance of surface near pH value in supporting both the growth and health of the algal component, with artificial concrete carbonation playing a key role in lowering the materials pH value and enhancing bioreceptivity. In a static, axenic laboratory growth experiment, the addition of nutrients onto the materials surface had a minor impact on bioreceptivity. Subsequent adhesion tests also revealed that a certain level of stress might enhance the biofilm's resilience to environmental pressures, such as water flow. Dynamic laboratory simulations with artificial rain showed that surface texture significantly influences biofilm adhesion, with near-surface porosity aiding in the retention of water and microorganisms and thereby promoting growth. Achieving an effective and lasting algal biofilm-based green facade system requires a careful balance between concrete surface pH value, material porosity and water retention.

Keywords: Bioreceptivity; Biofilm; Microalgae; Concrete; Carbonation; pH-value

Highlights

- The results gained using a multi-level approach to assess bioreceptivity of concrete show that for creating an effective and durable algal biofilm green façade system a balance between growth and vitality of the organisms and adhesion to the substrate must be achieved.
- For making laboratory experiments representative and reproducible organisms for model biofilms must be carefully selected regarding their capabilities to interact.
- Concrete substrates with low pH value, surface porosity in the microscale and increased roughness for altering the water flow over the surface proofed to enhance bioreceptivity.

1 Introduction

When Building envelopes are the interface between solid material, biosphere, and the atmospheric environment. They are a natural habitat of subaerial biofilms and differ in their bioreceptivity, meaning their proneness to be colonized by microorganisms (Guillitte, 1995; Sanmartín, Miller, Prieto, & Viles, 2021). While the interactions between organisms and building materials have traditionally been explored in the context of biodeterioration, the deliberate enhancement of these materials' bioreceptivity represents a relatively recent research focus. Shifting the focus from preventing microbial growth to embracing the potential benefits of biofilms on manmade surfaces marks a much-needed change in perspective. Integrating nature into urban environments opens new aesthetic possibilities and reduces reliance on harmful biocides (Manso, Calvo-Torras, De Belie, Segura, & Aguado, 2015; Mustafa, Prieto, & Ottele, 2021; Tran et al., 2012; Veeger, Prieto, & Ottelé, 2021). Considering the globally decreasing biodiversity (McKenzie, Jones, Seega, Siikamäki, & Vijay, 2025) and the importance of an intact, diverse microbiome for urban health, it is even more imperative to find ways to integrate nature into cities (Rotondi, Gironi, Ciufo, Diana, & Lucibello, 2024; Stefanova, In-na, Caldwell, Bridgens, & Armstrong, 2021).

Laboratory experiments of microbial growth on material offer the possibility of accelerating biofilm development with respect to natural biofilms. Moreover, controlling the climatic boundary conditions allow to focus on particular aspects of material bioreceptivity on biofilm development, and biofilm interaction with the material. However, there are a multitude of experimental designs (Fuentes, Vázquez-Nion, & Prieto, 2022) which hardly allow to compare results from different research groups. Therefore, we propose to use a model dual-species biofilm (A. A. Gorbushina, 2010; A. A. Gorbushina & Broughton, 2009) and a systematic, multi-level approach that allows to analyse whether the results are consistent with the results from outdoor weathering. In the presented research we used this methodology to investigate which parameters of concrete substrate facilitate growth on vertical samples and ensure durability under abrasive forces.

2 Materials and Methods

For assessing bioreceptivity a multi-level approach is used. The substrates are comprised of cementitious materials, which act as façade proxies. In both experiments a novel multi-species biofilm, comprised of the alga *Jaagichlorella* sp. and the fungus *K. Petricola*, is implemented. Pulse Amplitude Modulation Fluorometry (PAM) is utilized to quantify algal biomass development and photosynthetic activity (Eggert, Häubner, Klausch, Karsten, & Schumann, 2006; von Werder, Venzmer, & Černý, 2013). Whereas the first experiment comprised the analysis of chemical parameters in a sterile experiment, the second experiment focused on the impact of the surface texture and surface porosity.

2.1 Pulse Amplitude Modulation Fluorometry

The study used a MINI Version IMAGING-PAM M-Series (Heinz Walz GmbH) with blue light and Imaging Win v2.56zn software. Measurement settings were light intensity 3, saturation pulse 1, and gain 1. Dark-adapted base fluorescence (F_0) served as a biomass proxy, while maximal quantum yield (F_v/F_m) indicated photosynthetic efficiency. ImageJ was used to quantify algal coverage.

2.2 Concrete Substrates

Experiment 1 tested a mortar made of CEM I and standard sand according to DIN EN 196-1 with altered w/c ratio of 0.6. Surface roughness was increased by acid washing and part of the samples underwent accelerated carbonation treatment (Table 1, Figure 1).

Within experiment 2, an Ultra High-Performance Concrete (UHPC) was imprinted with four different surface textures, using expanded clay, a textile, and structured formwork moulds (Table 1) which resulted in different water retention, roughness, and porosity characteristics (Table 2). For roughness measurements a laser based profilometer (optical sensor system by Form + Test) was implemented.

Hygric performance was measured with NMR (NMR Mouse), water contact angles (DataPhysics OCA) and sorption coefficient (adapted from DIN EN 13057). For measuring the contact angle and the roll-off angle droplets of 10 µl were used. The combination of methods allows to determine between absorbed water and the actual bioavailable water stored in the upper most layers accessible for organisms.

Determination of the surface pH required a new test setup, which reflects leaching of the alkaline pore solution from within the concrete. 3 x 1 cm disk shaped concrete samples were sealed within a small container, and a fixed amount of demineralised water (10 mL) was added to the surface. The pH of the water was then measured over time.

Table 1: Material composition overview.

Specimen	Composition	Treatment
CEM 1_AW	CEM I Sand 0/2 mm w/c = 0.6	Acid washed
CEM 1_AW_C		Acid washed, Carbonation for 160 days, 4% CO_2, 21 ± 2°C, 60 ± 10% RH
BLANCO	NANODUR® 5941 Sand 0/2 mm w/c = 0.19	smooth formwork
VINIDUR		Structural matrix made of Vinidur
TEXTILE		Textile integrated in formwork
CLAY		Expanded clay integrated in formwork

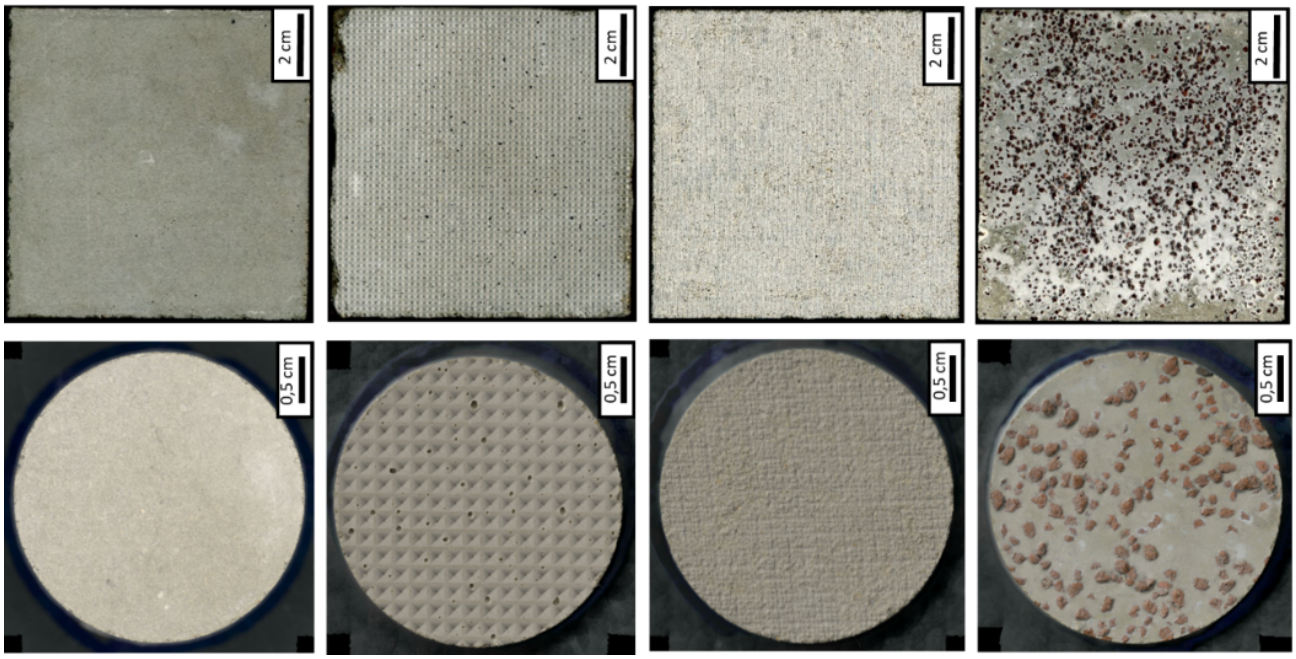

Figure 1: Overview of the produced sample, from left to right: Blanco, Vinidur, Textile, Expanded Clay. The upper row shows digital microscopy images (sample diameter: 3 cm), the lower row shows scans of the respective surface as a 10 cm x 10 cm sample.

Table 2: Characterization of UHPC substrates.

Specimen	Surface roughness [µm]	Sorption coefficient after 2 h [kg/m^{2}h0.5]	water retention in the uppermost layer measured by NMR	Water contact angle / roll off
BLANCO	25.53+/- 8.5	0.01	low	< 90°/droplets of 10 µl adhere in vertical position
VINIDUR	65.92+/- 25.6	0.02	low	
TEXTILE	62.38+/- 7.0	0.06	high	water is absorbed by the material surface
CLAY	98.53 +/- 23.9	0.03	intermediate	

2.3 Model Biofilm

The selected algal strain, *Jaagichlorella* sp. (AB13.021D5; Beck et al., in preparation), is a subaerial green coccoid micro-alga that was isolated from a north-west facing façade in Berlin, Germany. It is well adapted to living on surfaces in direct contact with air under low liquid moisture conditions, making it an ideal candidate for the experiments.

The selected fungi, *K. petricola*, is known for colonising stone surfaces under harsh environmental condition and has a neutral interaction with micro-algae.

2.4 Experiment 1: Growth Chamber

At the first stage chemical properties were analysed under controlled sterile conditions within a growth chamber (Fig, A). The concrete samples were singularly fixed inside a plate using agar, which provides a high humidity during the experiment, and inoculated with the test biofilm. The alga *Jaagichlorella* sp. was inoculated onto the sample surface alone (8.85×10^5 cells/cm^2) or in combination with the fungus *K. petricola* (8.85×10^3 cells/cm^2). Afterwards the plates were sealed for sterility and for humidity stability and analysed in regular intervals. The impact of surface pH and nutrient composition were investigated using a factorial experiment. Biofilm adhesion was tested through hydrodynamic stress to evaluate resilience (Fig, B).

Nutrient Preparation: To investigate the influence of nutrients on the microorganism performance, a nutrient coating was applied to the surface of the concrete samples prior to inoculation. A stock solution of Bold's Basal Medium (BBM) for freshwater alga was prepared at 1X concentration with ultrapure Milli-Q® water (Merck, Germany). To approximate optimal growth conditions, 88.5 µL/cm^2 of BBM is added to each sample and allowed to dry. For consistency, the same amount of ultrapure water is added to the control samples.

Factorial Experiment: The experiment in the growth chamber contained 3 factors (pH, microorganism, nutrients) varied over 2 levels resulting in a 23 full factorial design (Table 3). For the pH factor, the low and high levels correspond to non-carbonated and carbonated concrete, respectively. For the microorganism factor, the levels are *Jaagichlorella sp*. alone and *Jaagichlorella* sp. combined with *K. petricola*. For the nutrients factor, the levels are no nutrients (water) and BBM. Each run is triplicated, and all runs are randomised.

Determination of surface pH: After 30 min the pH measured on the carbonated surface was about 8.1 compared to 9 measured and on the reference. The evolution of the pH value over time shows that for both surfaces the pH increase due to leaching for about 30 hours (
Figure).

Table 3: Factorial Design overview.

Run	Factor		
	pH after 0,5 h	Microorganisms	Nutrients
1	8.1	*Jaag.*	BBM
2	8.1	*Jaag./Knuf.*	BBM
3	9	*Jaag.*	BBM
4	9	*Jaag./Knuf.*	BBM
5	8.1	*Jaag.*	Water
6	8.1	*Jaag./Knuf.*	Water
7	9	*Jaag.*	Water
8	9	Jaag./Knuf.	Water

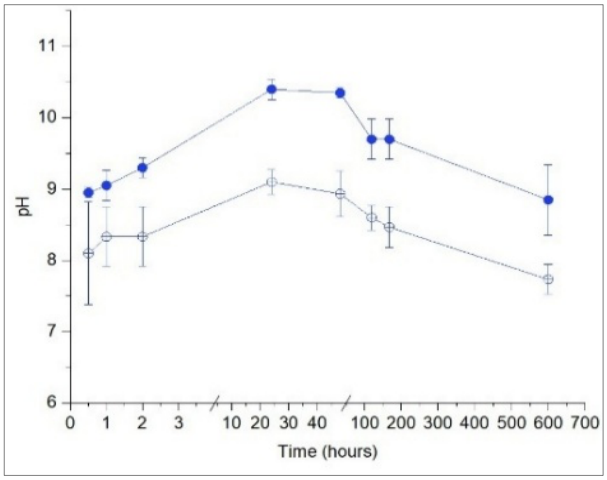

Figure 2: Development of pH over time.

Data Analysis: For statistical analysis, the change in F_0 and F_v/F_m from the beginning to the end of the experiments (ΔF_0 *and* $\Delta F_v/F_m$) are used to quantify the factor and interaction effects. Effect estimates are calculated, along with formulation of a full factorial model as shown in Equation 1:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 + \beta_{123} X_1 X_2 X_3 + \epsilon \quad (1)$$

where Y is the response variable, X-values correspond to the factors (*X1* = pH, *X2* = nutrients, *X3* = microorganism), β-coefficients represent the expected change in response per unit change in factor value when all remaining factors are held constant, β_0 is the overall average response of all runs, and ϵ is the error.

Analysis of variance (ANOVA) is carried out using DesignExpert® to determine which factors or interactions are statistically significant. The model is then refined to remove any non-significant terms based on a p-value < 0.05.

2.5 Experiment 2: Laboratory Set-up

At the second stage the impact of the surface texture and surface porosity are assessed using the same material (UHPC) imprinted with different textures. Prior to the weathering experiment, samples were autoclaved and then inoculated under sterile conditions with 10^7 algal cells. Algae were dropped onto the surface as a 5 µl suspension, resulting in a small initial area covered by algae and enabling to monitor the growth easily. After 2 days of algae acclimating themselves to the substrate in a climate chamber, samples were transferred to a controlled, but non-sterile weathering setup with sample inclination and an irrigation system. The day/night cycle of 12h/12h was implemented by LED arrays. The irrigation system ran on deionized water and was set to irrigate every 3h for 1 minute during the daytime of 12h. Additional fog humidification ensured sufficient humidity of at least 80 % RH during the day and at least 90 % RH at night (Fig, C).

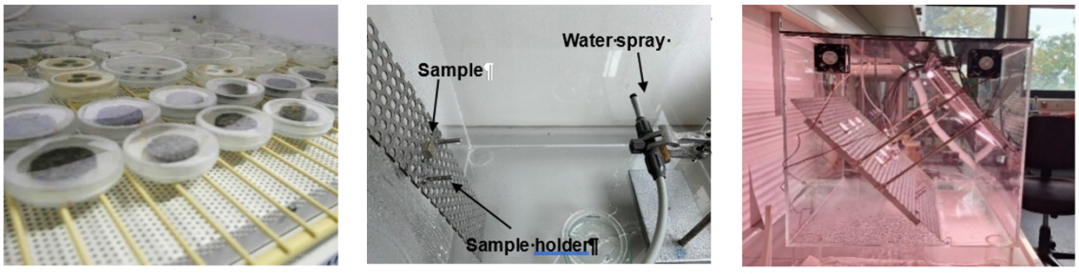

Figure 3: Test set-up for assessing bioreceptivity: A samples in the growth chamber, B: adhesion test, C: laboratory set-up.

3 Results

3.1 Experiment 1: Growth Chamber

The change in F_0 values can be seen in detail in Figure . While the algal biomass on the carbonated samples increases over the time of the experiment, on the non-carbonated samples there is a rapid reduction of biomass from the start. Only after 20 days algal growth increases again on all samples except sample 8. The data analysis shows for the inclusion of nutrients a close to a significant effect and when the carbonated data is isolated, a significant positive effect can be observed for $\Delta F_v/F_m$ (not shown). Interaction terms are non-significant in both cases and have been removed from the ΔF_0 model during refinement (Table 4).

Adhesion of the biomass – measured as ΔF_0 (before and after application of the water spray) correlates with the vitality of the organisms before application of the water spray. Biofilms showing a low vitality adhere better to the surface than biofilms showing higher vitality reflected in higher variable fluorescence F_v/F_m. (Figure).

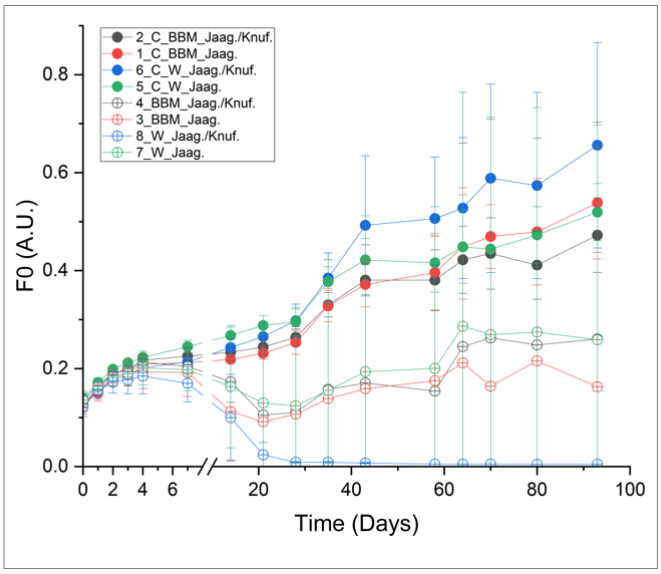

Figure 4: Change in F_0 over time.

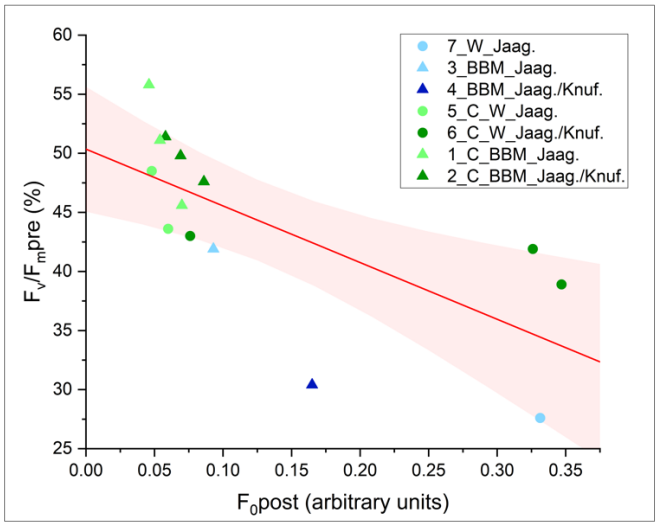

Figure 5: Comparison between F_v/F_m (before spray) and ΔF_0 before and after the spray.

Table 4: Summary of ANOVA for the ΔF0 model.

Source	Sum of Squares	Mean Square	p-value
Model	0.8107	0.2702	0.0196
A-pH	0.8095	0.8095	0.0022
B-Microorganism	0.0022	0.0022	0.8546
C-Nutrients	0.0001	0.0001	0.9733
Error	1.06		

3.2 Experiment 2: Laboratory Weathering

Over the course of the laboratory weathering, the UHPC samples exhibited strong differences in their bioreceptivity. Figure 6 shows an example of the chlorophyll fluorescence data on a Clay sample. Within the first three weeks, the fluorescence parameter F_0 correlated to biomass declines as algae are washed from the surface by irrigation. After a lag phase of ~1.5 months, remaining algae cells caught in the structure are acclimated to their new environment and start growing. This results in an increase in chlorophyll fluorescence parameter correlated to biomass (F_0) measured at the later stages of the weathering experiment.

These images (Figure 6) were also used for ImageJ analysis calculating the area coverage (Fig). Substrates Blanco and Vinidur, which are characterized by hydrophilic behaviour and low water absorption and retention did not provide sufficient potential for the algae to attach and permanently anchor themselves to the materials. As algae are washed off quickly, data shows a fast decline in biomass within the first 9 days and no recovery over the duration of the experiment.

The other two surfaces, Clay and Textile did show an initial decline, but after a lag phase a subsequent increase in biomass. As these are the two structures providing porosity, they offered better attachment points for the algae to withstand the shear stress exerted by the irrigation system.

The roughness of about 60 µm characteristic for both Vinidur and Textile seems to offer no protection against the abrasive irrigation and needs to be supplemented by a texture in the size of the organisms, which is achieved in the case of Textile substrates through porosity.

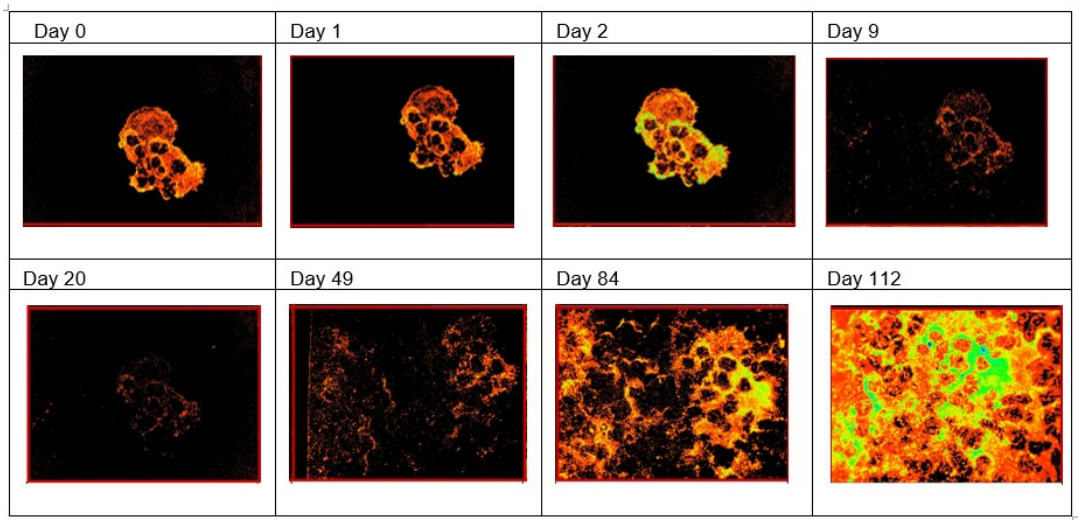

Figure 6: Chlorophyll a fluorescence (F0) as displayed in the Imaging PAM software of the sample Clay 6 over the course of 4 months. Intensity can be correlated to biomass. All pictures refer to an area 2.4 x 3.2 cm².

This data confirms that the surface structure strongly influences attachment and growth of organism. Moreover, it shows Textile performs well due to its water retention and porosity and that these factors

have a bigger impact than roughness on larger scale as implemented in Vinidur. Curiously, Clay performed differently than expected. Instead of growing on the expanded Clay, algae grew in between the clay aggregates on the bare concrete (Figure 6). The aggregates do not seem to be a preferable habitat, but rather to influence the flow of water on the surface and thus protect algae.

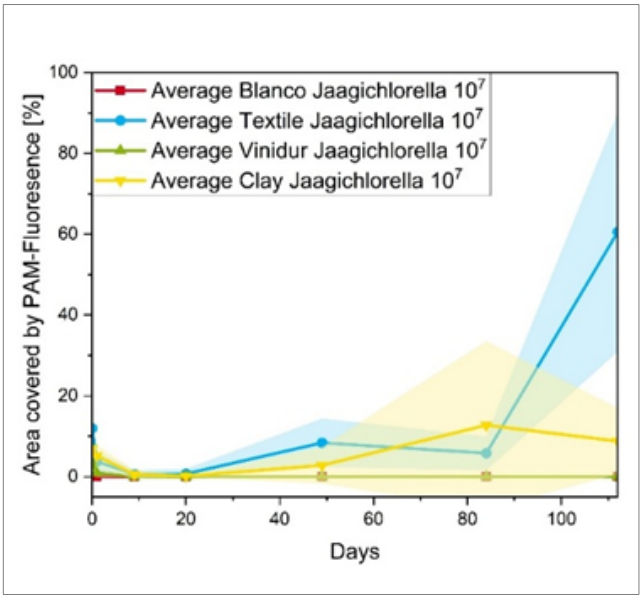

Figure 7: PAM-F Data over the duration of four months. The F_0 biomass values were analyzed, and the area covered by chlorophyll fluoresce in % was calculated with ImageJ.

4 Conclusions

Research on bioreceptive materials has greatly increased over the last years, yet significant challenges persist due to the interdisciplinary nature of the field. With the aim to establish a comprehensive framework, a structured three-stage approach to assess bioreceptivity has been developed.

The initial stage involved axenic experiments to assess the chemical compatibility between materials and algae and the effect of adding nutrients. The results for conventional mortar based on Portland cement highlight the critical role of pH in both the growth and health of the organisms, with carbonation being crucial for the successful colonization of cementitious materials. The impact of the addition of nutrients is not correlated to improved growth but reflected in the data on photosynthetic efficiency. The fact that an interaction effect between pH and microorganisms could not be proofed by the ANOVA analysis might be because the pH of the substrate was in an acceptable range from the start. The same test using a different substrate with a higher initial pH showed significant interaction indication that interaction of the organisms is stress dependent. In addition, adhesion strength testing suggests that some stress may be beneficial for the organism in terms of increasing resistance to hydrodynamic stress. This finding could explain why algal biofilms cultivated under highly favorable lab conditions often fail when exposed to outdoor environmental conditions. It is evident that a balance between photosynthetic efficiency, growth and biofilm adhesion must be achieved to create an effective and durable algal biofilm green façade system.

In the second stage it was assessed how the physical material properties influence bioreceptivity under controlled laboratory conditions. Results for UHPC substrates differing in their surface texture showed a crucial influence of physical material properties when it comes to attachment and the successive growth of algae. Surface structures with increased roughness could profoundly alter the flow of water over the surface and protect the organisms from shear stress. Substrates with surface porosity in the microscale proofed to significantly enhance bioreceptivity. After a lag phase in which the algae

transferred from the liquid acclimate to the new environment, these structures proved to facilitate growth. In contrast on the dense and smooth surfaces the algae were not able to adhere once subjected to shear stress.

The third stage of the developed framework involves still pending results from a perennial outdoor weathering of the UHPC samples. This data will be evaluated and compared with the results of Stage 1 and Stage 2, to determine whether the accelerated weathering tests deliver results that are representative of natural weathering. By implementing this framework, we aim to enhance comparability across studies and systematically facilitate advancements in the field of bioreceptive materials design.

If the methodology proofs to be reliable optimal pH ranges and specific porosity and texture characteristics for bioreceptive substrates can be determined in further systematic tests and maintenance requirements for real facades in terms of irrigation and nutrient supply can be defined. By integrating enough stress in the laboratory experiments we aim to further assess the long-term durability under outdoor weathering. For scalability and implementation of bioreceptive façades we are closely cooperating with architects.

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Ethical Approval Declaration
The study was conducted in accordance with established standards for research integrity and ethics.

Data Availability Statement
Data sets generated during the study are available from the corresponding author on reasonable request.

Conflicts of Interest
The authors declare no conflict of interest.

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