



Microalgae bio-reactive façade: biotechnological, building, and indoor environmental indicators in contrasted climate zones, the US as a numerical case study

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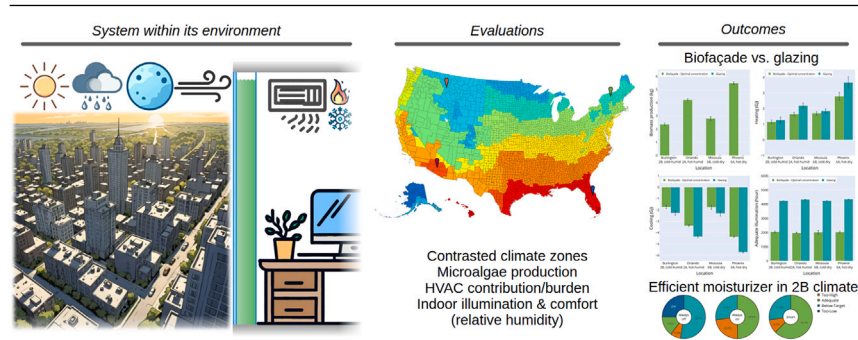
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HIGHLIGHTS

- Biofaçades are considered a potential synergy between buildings and microalgae.
- The system is studied in the case of an office building and a household in the US.
- Contrasted climate zones are investigated (hot vs. cold, dry vs. humid).
- Results show consistent production and HVAC load patterns over the territory.
- Biofaçades can substantially improve relative humidity comfort in dry-hot zones.

GRAPHICAL ABSTRACT



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ABSTRACT

This work investigates microalgae biofaçade performance in a holistic manner (biotechnological productivity, building energy use, indoor environmental indicators). These investigations are led using a thermal-biological model and weather data obtained from NREL over the years 2019 to 2023. To challenge the different findings, four locations, in four different US climate zones, are considered: Burlington, Vermont (6 A, cold-humid), Orlando, Florida (2 A, hot-humid), Missoula, Montana (6B, cold-dry) and Phoenix, Arizona (2B, hot-dry). Both office building and household implementations are covered, with South and North orientations. Hot regions allow for almost doubling microalgae production (from about 2.5 to 5 kg/year/module, South orientation). From a thermal standpoint, biofaçade modules offer a slight advantage compared to conventional double-glazing in the case of an office building implementation. This difference (0.42 ± 0.07 GJ/year/module) is consistent across climate zones and is mainly driven by the summer shading effect offer by the microalgae. Regarding indoor illumination, microalgae development is perceivable by occupants' as a culture spans from 6 to 30 days (consistent for all the climate zones). Finally, biofaçade modules can improve indoor relative humidity comfort climate-wise. While irrelevant in 6 A and 2 A zones, it is worth considering in 6B zones, and very pertinent in 2B zones, as it drives adequate humidity moments from 19.7% to 62.5% of the time.

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1. Introduction

Microalgae, defined as freshwater or marine water photosynthetic microorganisms, play several roles in today's world. Their main and most ancient contributions are to our atmosphere, with about 50% of the annual oxygen production [1], and to our ocean, with a key role in its biogeochemical balance [2,3]. Over the past century, mankind has started to domesticate them. In the previous decades, they have emerged as crucial auxiliaries in wastewater treatments [4], with high nitrogen and phosphorus fixation capabilities [5,6]. Nowadays, they appear as promising candidates for producing medium-value commodities, such as quality food and feed [7,8], and high-value compounds [9], such as pigments with demonstrated health benefits, for example, lutein [10]. Nevertheless, commercial applications of microalgae are struggling to expand beyond their historical cradles: aquaculture and food, in some niche markets, such as Japan.

One of the reasons hindering microalgae's success is their production cost. Indeed, while optimistic forecasts predict that the production cost could fall to around 4 USD/kg [11], one should bear in mind that such feats are only possible in very specific cases: large pieces of land with adequate weather (high sun resources, low cloud cover, ...) and access to medium-grade CO₂ (non-toxic fumes, fermentation gaseous streams, ...). Given the limited possibilities for such ideal setups, alternative massification approaches must be explored. Among them lies synergizing microalgae cultivation with other systems to lower the associated capital expenditure and, consequently, their production cost. With this objective in mind, scholars and engineers came up with the idea of integrating microalgae photobioreactors into building façades (in short biofaçades).

This emerging technology belongs to the group of advanced architectural solutions [12,13], which delivers mutual benefits to both microalgae and building systems. On the microalgae side, integrating culture vessels into buildings will reduce the cost of vertical support, while providing utilities (e.g., water, thermal regulation), and potentially nutrients (e.g., carbon dioxide reclaimed from the building boiler). On the building side, integrating photobioreactors will provide shading, enhance thermal comfort by better modulating incident heat [14], reduce pollution emissions [15], generate energy [12], and offer aesthetic enhancements [16].

Yet, the road is still long before the megalopolis buildings are covered by biofaçade modules. Nevertheless, preliminary works have opened the way with both experimental and numerical investigations. Experiments have mainly dealt with isolated modules (not integrated into a host building) and delivered answers to basic questions such as thermal performance (with U-values as low as 3.84 W/m²/K reachable with adequate design) [17] or biomass productivity (of 7.68 g/m²/d in France [18], or 0.314 g/L/d in Colombia [19], both in ideal cases). On the other side of the spectrum is the case of the BIQ house field trial in Hamburg, Germany, set up for an architecture exhibition. The residential building was equipped with 185 m² of biofaçade [20]. Even though short-lived, this large scale experiment allowed researchers to gather valuable measurements of the microalgae photoconversion efficiency (a.k.a. photosynthetic efficiency, 4.4%, comparable to laboratory studies 4.34% to 5.65% [21–23]), and validated building occupants acceptance of the technology.

Numerical models were also used to tackle questions such as module design optimization accounting for location specificity (advising for double-glazing, and the use of specific coatings favoring visible light over InfraRed radiation [24,25]). The module integration was also investigated numerically to devise between conventional vs. double skin façade integration [26,27], or straight vs. free-form façade [28]). Thermal-biological coupling was also analyzed by simulating building integration [29,30], accounting for the impact of weather (locally, [30,31], and at country scale [32,33], showing relatively uniform performance over a country—France). Numerical tools also delivered insights on visual comfort and aesthetics [14,34], showing some limits of the

technology (modules should at most cover half of the glazed façade to avoid visual discomfort of the occupants).

Still, some shortcomings of the previous investigations are to be noted and addressed. First of all, the previous country-scale evaluation was led at a somewhat small scale (France) [33]. While insightful when it came to building construction dynamics and possible deployment rates, it fell short in terms of climate contrast. Investigations on a larger, more contrasted scale are therefore needed to evaluate the system's potential thoroughly. Second of all, overall system performances are usually reported in a segregated manner: either building thermally-oriented (U-values), or microalgae production-oriented (areal and volumetric productivities). Lastly, while numerous dimensions of the occupants' comfort have been investigated, they mostly focused on light-related comfort (overall illumination and glare), and relative humidity has been investigated by only a few scholars. It is all the more surprising as a microalgae biofaçade module can very easily act as an air moisturizer. Indeed, while some reviews suggested this possibility [35,36], only two experimental studies investigated it in mini-models [16], with one of them resorting to setups raising questions about their similarity with actual housing (air-tight enclosure of 100 L for a 2 L external photobioreactor) [37].

Acknowledging these limitations, this work aims to address these three dimensions (building, microalgae, and occupants' comfort) simultaneously. To do so, it assesses the system performances numerically in terms of biotechnological output, building HVAC load reduction (or increase), and occupant comfort (based on relative humidity and visual perception). Also, it addressed the question of the contrast by systematically examining four locations, in four different ASHRAE climate zones over the US (Burlington, Vermont—cold-humid—; and Orlando, Florida—hot-humid—; Missoula, Montana—cold-dry—; and Phoenix, Arizona—hot-dry—), which represents a step forward compared to previous single-location or low-contrast studies. The choice of a numerical investigation was dictated by practical reasons. First, it allows exploration of several locations over extended periods of time at a modest cost, as opposed to field trials, which are time and spatially constrained. Second, it can use readily available data, such as the NREL meteorological data, as opposed to field measurements, which are expensive, local, and sometimes flawed [38]. Third, given the cost of an experimental campaign, a priori numerical investigation is required to mobilize the funds necessary to lead field investigations, while concomitantly narrowing the range of relevant parameters and configurations.

2. System description & model

2.1. System design & operation

The module design is illustrated in Fig. 1. Key features are: a 1-inch thick reservoir hosting a *Chlorella vulgaris* culture, with a sparger at the bottom (supplying CO₂ and removing excess O₂). Double glazing is set before the culture compartment to harness more energy during the cold season. Indeed, low wintertime temperatures may prevent microalgae from processing all the light they capture, incidentally limiting year-round productivity. This is all the more important as biofaçades are vertical systems, meaning that they collect more light during winter. This trait is particularly beneficial as it helps to limit the possibility of overheating during the summertime. In terms of specific details, while some double-glazing unit designs can be found in literature (e.g., Weir and Muneer [39]), it was decided to equip the biofaçade modules with state-of-the-art double-glazing units actually used in the US. The model retained for this study is the SunGuard™ SNX 62/27 unit, made of 6 mm glass, a low-emissivity coating, 12.7 mm of pure air, and 6 mm of glass. Its performances (visual transmittance of 64%, SHGC of 0.27, LDG of 2.40, U-value of 1.62 W/m²/K) makes it ASHRAE-compliant in zones 6 A and 6B (requiring an SHGC below 0.38, a LDG above 1.10, and a U-value below 1.76 W/m²/K) and almost compliant (0.02 SHGC

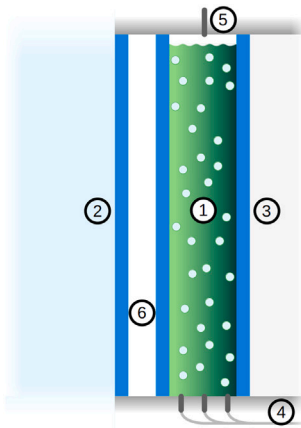


Fig. 1. Left-schematic representation of possible microalgae biofaçade design (the aspect ratios and compartment thicknesses are illustrative). 1-microalgae culture reservoir (1-inch thickness, 2-outward glazing layer (glass pane thickness-6 mm), 3-inward glazing layer (glass pane thickness-6 mm), 4-gas sparging system (0.2 Vessel volume per Minute), 5-Vent, 6-Double glazing (air layer thickness-12.7 mm). Right - Drawing of a potential integration into an office building façade.

difference) in zones 2 A and 2B (requiring an SHGC below 0.25, a LDG above 1.10, and a U-value below 2.56).

The culture can be controlled in two ways: batch mode and continuous mode. In the first mode, it is operated in such a way that whenever the microalgae concentration reaches a prescribed concentration, 80% of the culture compartment is flushed and replaced by fresh medium. By nature, this mode of operation induces an indoor illumination cycling, with progressively less light passing through as the culture grows. In the second mode, fresh medium is injected continuously to ensure a slight dilution of the same order of magnitude as the growth. Consequently, the concentration within the culture compartment is constant over time. From an indoor illumination perspective, this means that the transmitted light fraction is also constant, and no culture-induced modulation of the day/night cycle can be perceived.

2.2. Host buildings

Two possible implementations were explored in this work. First, a tall building located in the city center was considered, referred to as the *office building*. In this case, the biofaçade module is located about 20 meters above the ground (ensuring unrestricted access to sunlight) but within an environment subjected to an Urban Heat Island phenomenon. From a thermal point of view, the office building internal temperature is assumed to be regulated at 22 °C, as the US Occupational Safety and Health Administration (US OSHA) advises between 20 and 24.5 °C [40]. This assumption agrees well with the survey reported by Salthammer and Morrison [41]. Furthermore, the building is considered lit with an intensity of 30 foot-candle (from 7 am to 9 pm, 5 days a week), as it is the recommendation of the US OSHA for office environment [42]. Finally, the module height is 4 meters, which is the standard floor height in modern office buildings.

The second implementation considered is a residential building located in the suburban area, referred to as the *household*. In this configuration, the building might be subjected to an overcast shadow from a neighboring building across the street (8 meters tall, 25 meters away). The building is assumed not to be impacted by an Urban Heat Island phenomenon. Its indoor temperature was assumed to follow a daily time-fluctuating pattern based on literature (see Appendix) in addition to a dependence on outdoor temperature. An indoor lighting (of 30 foot-candle) was assumed to be on from 6 am until dawn and from dusk until 10 pm. Finally, the module height is taken as 3 meters. For these two possible implementations, two orientations were evaluated: due South and due North.

2.3. Locations & weather data

A microalgae biofaçade is exposed to external weather conditions; thus its capabilities must be investigated under different climatic circumstances. To this end, the ASHRAE classification of the US climate was used for guidance in picking indubitably contrasted test cases (cold vs. hot, and humid vs. dry). Therefore, this study chooses Burlington, Vermont (44.476, -73.214), Orlando, Florida (28.545, -81.333), Phoenix, Arizona (33.448, -112.075), and Missoula, Montana (46.872, -113.994), as model cities. These cities are located in the ASHRAE 6 A (cold-humid), 2 A (hot-humid), 6B (cold-dry), and 2B (hot-dry) climate zones, respectively (Fig. 2). The weather data associated with this place were obtained from NREL, National Solar Radiation Database (NSRDB), “USA & Americas (10, 30, 60min / 2km / 2019-2023)” dataset, with a time resolution of one hour, last accessed on June 15th, 2025. This dataset spans over the 2018–2023 period. Still, out of this dataset, the following simulations cover the 2019–2023 (both ends included) period, as the year 2018 was used for model initialization.

2.4. System model

The system model is built around three intertwined compartments: thermals, illumination, and biology. These building blocks are introduced, discussed, challenged, and applied in a set of previous articles (dedicated to the thermal and illumination models [24,25], then their coupling with biology [29,32]). The overarching philosophy is that temperature (computed first) and illumination (computed second) modulate biological activity (computed third). These three components will be presented synthetically here, while all the equations and associated parameters are made available in the Supplementary Materials.

In a nutshell, for each time step, the thermal model computes microalgae reservoir temperature by accounting for absorbed and emitted convective-radiative heat fluxes. Two types of heat fluxes can be distinguished: weather-dependent and weather-independent. The first group comprises direct sunlight, radiation from and towards the sky (modulated mainly by the cloud cover). They are described using the model proposed by the Illuminating Engineering Society, which considers solar time, position on Earth, cloud cover, and orientation [43]. The first group also encompasses radiation towards the surroundings (modulated by the surrounding environment temperature and a potential Urban Heat Island effect for office building implementations only). Finally, this group also accounts for the convective-conductive exchange with the outdoor air (modulated by outdoor air temperature, wind velocity,

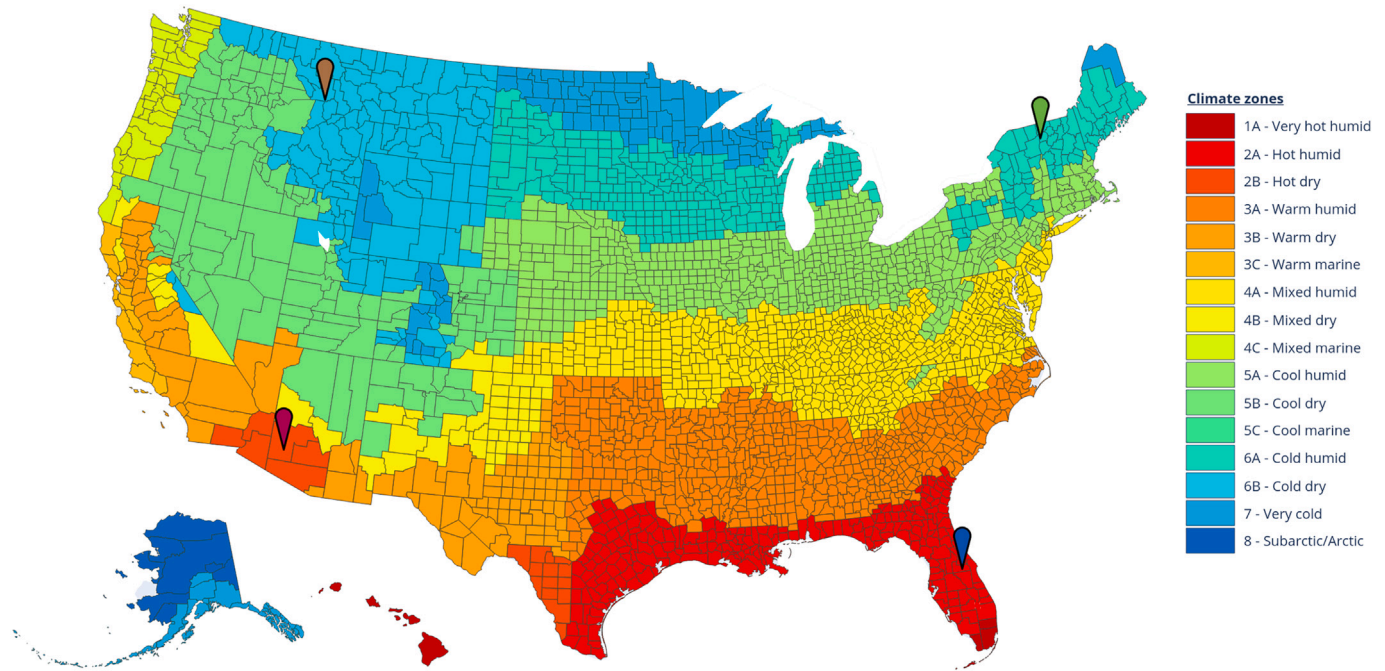


Fig. 2. ASHRAE climate zones and investigated cities locations (●).

and direction). The second group comprises radiation from and towards the host building, the convective-conductive exchange with the host building air, the heat inflow carried by the gas sparged into the culture, and the heat extracted by the vented gas.

The illumination model aims to quantify the amount of photosynthetically active radiation captured by the microalgae (driving proliferation) and the average illumination within the module (driving pigment content acclimation and photoconversion efficiency). Sun and sky contributions are obtained thanks to the Illuminating Engineering Society model. Illumination coming from the inside of the building is then added to the natural light contribution. Furthermore, light quality, *i.e.*, colors, is described by splitting it into three bands: blue, green, and red. For each band, microalgae exhibit different optical properties, hence different light penetration. Coefficients needed for these calculations are derived from the literature [44,45].

Once temperature and illuminations (absorbed energy and volume-averaged light intensity) have been computed, the biological model deploys mass and energy balances to describe microalgae proliferation. The amount of harvested actinic energy allows for computing the quantity of microalgae generated (based on the cells' Higher Heating Value, assuming all other substrates are supplied in excess). In addition to growing, microalgae acclimate to the illumination conditions by changing their pigment content (increasing under low light and decreasing under high illumination). Cell maintenance is also accounted for with a difference between the day (light respiration) and night (dark respiration) [23]. Finally, cell metabolism as a whole (proliferation, maintenance, and pigment expression) is modulated by temperature [46]. Low temperatures reduce cell metabolism but do not damage the cells. On the contrary, high temperatures lead to a less efficient metabolism and can even harm the cells if excessive (irreversible denaturation of proteins and DNA [47]). On top of this, photosynthetic efficiency is also modulated by volume-averaged light intensity within the culture compartment, as higher light intensity leads to lower photoconversion efficiency.

Once the calculations are completed, a new time step starts with updated values of the microalgae concentration and cell pigment content, which will lead to a complete recomputation of the

absorbed power (heat and actinic) as well as volume-averaged light intensity.

3. Investigated parameters

3.1. Microalgae productivity & indoor illumination

A microalgae biofaçade being a hybrid system, its performances are to be evaluated both as a photobioreactor and glazing. However, these performances are intertwined. For example, a high microalgae concentration is beneficial from a biotechnological perspective (high productivity and ease of harvest) but detrimental from a building perspective (no light passes through). On the contrary, a low microalgal concentration lowers biomass production, hinders cell harvest, but increases solar heat gain in winter. Therefore, a systematic screening of the effect of the microalgae concentration is required to identify trade-offs. The tested concentrations ranged from 0.05 g/L (very dilute and translucent) to 5 g/L (quite concentrated and opaque), for two modes of cultivation (batch and continuous).

To lead this investigation, biotechnological performances were qualified, on a yearly basis, as the amount of microalgae produced by the system (in kg). Glazing performances were computed over three dimensions: the period of adequate lighting offered by the biofaçade (defined as the total duration for which light passing through features an intensity of at least 30 foot-candle - in hours - designed as an easy-to-compute proxy for spatial Daylight Autonomy, see next section), the heat gain offered by the system in winter (in GJ), and its possible contribution to building cooling in summer (in GJ). Of these four indicators, the first two (biomass and light intensity) are straightforward to assess. The two last ones need to be elaborated on. The effective heat gain offered by the system was defined as the heat (radiative or convective/conductive) passing through the biofaçade when needed during wintertime (from October 1st until April 1st, when heaters are on in cold zones). This heat was considered needed when the daily average indoor temperature was below 22 °C and at least 2 °C above the daily average outdoor temperature (only achievable by having heaters on). The cooling contribution was accounted for when the daily average outdoor temperature was at least 4 °C higher than the daily average indoor temperature, and

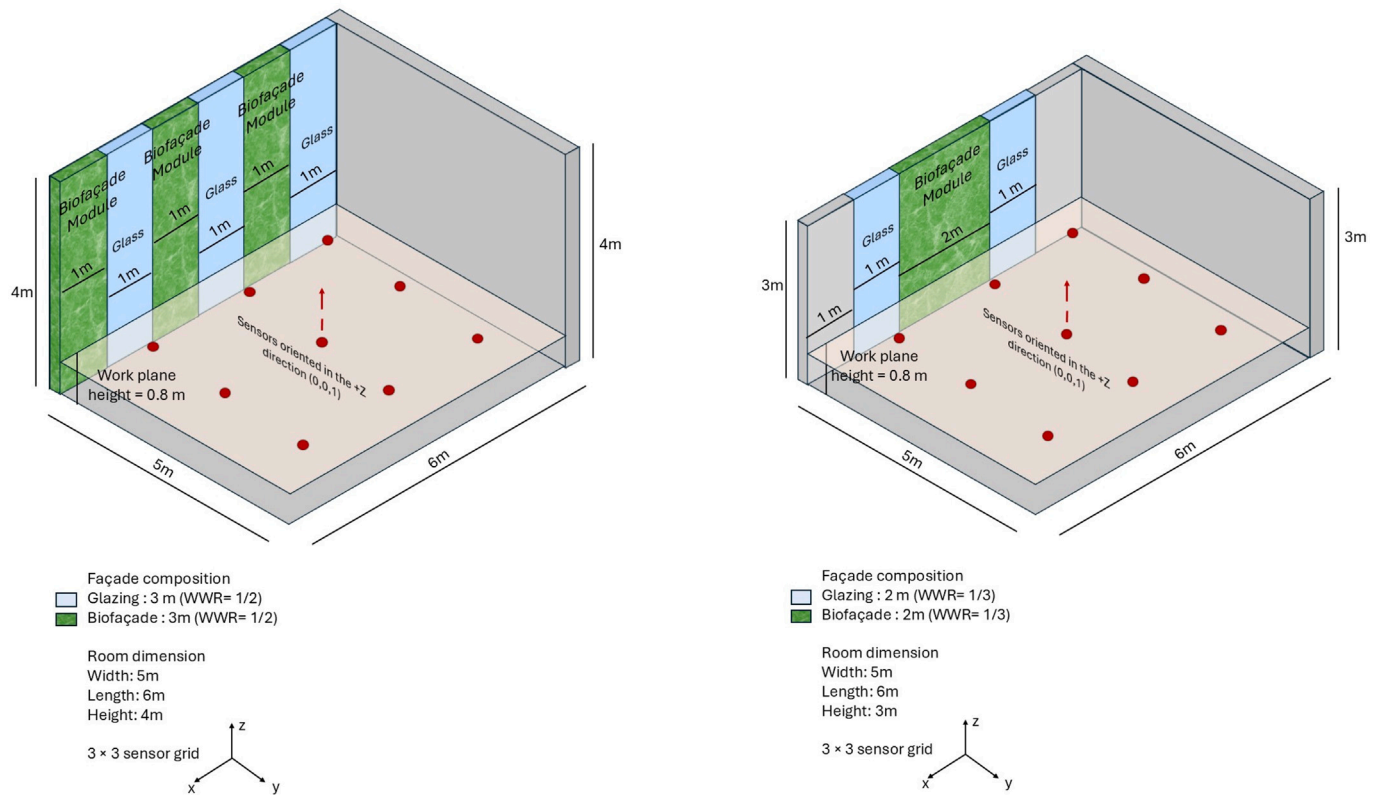


Fig. 3. Room geometries with biofaçade modules and glazing unit placements for the office building (left) and the household (right) implementations.

the indoor temperature of at least 24 °C (only achievable by having AC on).

3.2. Occupant visual comfort

While the previous section evaluated visual comfort with an easy-to-compute proxy, this section focuses on conventional performance indicators for key configurations identified with the above procedure. This choice was motivated by the fact that a detailed analysis is more demanding in terms of computational power, as all the moments over a year are to be simulated (30-minute resolution). To do so, a Python-based data processing algorithm was deployed to compute spatial Daylight Autonomy (sDA) and Useful Daylight Illuminance (UDI). It was applied to assess annual daylight availability in the household and office scenarios. These metrics are widely used to quantify indoor daylight performance by evaluating both daylight sufficiency and potential glare conditions.

The transmitted daylight through the biofaçade modules was obtained from the spectral outputs, which included red, green, and blue light components. These components were converted to photopic illuminance using the standard luminous weighting function. The daylight performance analysis was conducted for the four tested locations. The simulation dataset covered the period from 2019 to 2023; however, the analysis in this study was restricted to the year 2023 to represent a single climatic year.

The daylight simulation was conducted for simplified residential and office room configurations representing typical interior spaces. The office scenario consisted of a room with dimensions of 6 m × 5 m × 4 m (length × width × height), while the residential scenario had a height of 3 m with similar plan dimensions. The façade opening included a combination of microalgae photobioreactor panels and conventional glazing arranged horizontally across the façade. In the office configuration, the façade consisted of a 3-meter-wide algae panel and a 3-meter glazing section, while in the residential configuration the façade consisted

of a 2-meter biofaçade (two modules next to each other) and a 2-meter glazing section. This configuration represents a hybrid biofaçade system where daylight enters the interior through both the algae photobioreactor and the glazing window (Fig. 3), as advised by other teams [14].

To evaluate the spatial distribution of daylight within the interior space, a sensor grid consisting of nine work plane points (3 × 3 layout) was considered. To account for daylight attenuation within the interior space, illuminance levels were adjusted according to the distance of each sensor point from the façade using an exponential decay function. Indoor illuminance at each sensor point was estimated based on the transmitted daylight through the biofaçade for different façade orientations. As the façade configuration consisted of biofaçade modules and conventional glazing, the transmitted illuminance was estimated based on the visible transmittance of both components. The spatial Daylight Autonomy (sDA) metric represents the percentage of occupied hours when indoor illuminance exceeds 300 lux, while Useful Daylight Illuminance (UDI) categorizes daylight conditions into three ranges, including insufficient daylight (0–100 lux), useful daylight (100–2000 lux), and excessive daylight (> 2000 lux). The daylight analysis was performed for occupied hours between 08:00 and 18:00 to represent typical daytime building usage.

3.3. Relative humidity

In addition to contributing to thermal and visual performances/comfort, biofaçade modules can also act as an indoor relative humidity modulator. Indeed, the air sparged into the culture compartment (to supply CO₂ and remove O₂) can be seen as a source of moist air if directed towards the indoor of the building (as opposed to vented outside). Still, the relevance of its use to improve occupancy comfort is to be analyzed as an optimal range exists, as for any other comfort parameter (temperature, illumination, ...). According to ASHRAE, indoor humidity should be below 65% (standards 62.1-2016 and 55-2017) to reduce the

risk of microorganism growth while avoiding too low relative humidity, as it can cause discomfort, including skin dryness, irritation of mucous membranes, dry eyes, and increased static electricity. Departing for microbial safety reasons, it recommends a relative humidity between 30 and 60% to support thermal comfort and occupant productivity (standard 55-2020). Additionally, the Illinois Department of Public Health (IDPH) identifies an optimal indoor relative humidity range between 20 and 60%, cautioning that levels below 20% in winter and above 60% in summer should be considered unacceptable. It also points out that elevated humidity can contribute to the growth of mold, bacteria, and dust mites, which may exacerbate asthma and allergy symptoms. From these guidelines, it is possible to classify relative humidity as Too-Low (below 20%), Below-Target (below 40%), Adequate (between 40 and 60%), or Too-High (above 60%).

Once a classification has been established, evaluating the biofaçade modules' contribution requires taking several parameters into account: the outdoor air relative humidity (Y_{out}), the volume of the targeted space (V_{space}), the air renewal within this space (f), and the flow rate provided by the biofaçade modules (F). The first element is provided by the meteorological data. For the second, we assume a 8 by 12 m² office room, with a floor height of 3 meters (4 m including the utilities), leading to a volume of 288 m³. Space ventilation is assumed to follow ANSI/ASHRAE guidelines (Standard 62-2001), *i.e.*, is 0.35 Air Change per Hour (ACH) for living spaces, but not less than 15 cfm (7.5 L/s) per person. If 10 people are assumed to work in this space, the minimal ventilation is 75 L/s or 270 m³/h. Finally, the flow rate provided by the modules (operating at 2 Vessel Volumes per Minute and installed as 1 in 2, as advised by [14], on a 12-meter façade) would be 73.2 m³/h. All in all, this information can be combined into Equation (1) to yield the indoor relative humidity:

$$Y_{indoor} = \frac{Y_{out}(V_{space}f - F) + Y_{module}F}{V_{space}f} \quad (1)$$

whence Y_{module} to be 100% and the biofaçade flux to substitute part of the regular ventilation for a maximal effect. Of course, such a model negates the actual complexity of a real-world HVAC system. Still, it represents a first step towards analyzing the relevance of biofaçade modules as indoor moisture regulators.

In terms of operation strategies, three can be envisioned. First, the biofaçade is venting moist air outside. Hence, it does not modulate indoor air relative to humidity. This is the baseline scenario, referred to as *Always off*. Then, the opposite is also possible. The biofaçade modules release their air into the building. This scenario is referred to as *Always on*. Finally, one can imagine a system where the modules only supply air when needed (*i.e.*, outdoor relative humidity below 40%). This configuration is referred to as the *Smart* one.

4. Results

Numerous results were generated through the systematic screening of all the parameters. To ease their presentation and interpretation, the system's performance will be detailed in the case of a system located in Burlington, Vermont. First, batch mode will be evaluated from a biotechnological and thermal perspective. It will be followed by continuous mode. Then, the best of them will be retained to evaluate the occupant's perception of the culture and the quality of the indoor moisture adjustment. Finally, synthetic indicators will be used to compare all four locations.

4.1. Reference case, Burlington, Vermont

4.1.1. Batch mode

Fig. 4 presents the results from the systematic screening of the cell concentration for the four tested configurations: "household × office building" and "South orientation × North orientation", in batch mode. To limit the number of curves, heating and cooling contributions were

summed into HVAC contributions (positive values meaning energy savings, negative values meaning extra HVAC power needed to regulate indoor temperature). The shaded areas around the curves represent the standard deviation obtained from the year-to-year variations.

As a first comment, one can note that all the configurations exhibit a similar profiles. Biomass production features a rise-and-fall trend. The resulting indoor illumination declines following a somewhat S-shape curve. Finally, the HVAC contribution is only marginally affected by cell concentration.

Diving into the details, sizable differences between the setups can be commented on. First of all, when comparing South to North configurations, the North orientation is not operable above 2.7 g/L and consistently produces less microalgae than its Southern counterpart. In addition, its HVAC contribution is actually a burden (negative value) for the office building (about -0.60 ± 0.08 GJ and -0.75 ± 0.08 for South and North orientations, respectively). On the contrary, for the household, a biofaçade module contributes positively to the HVAC (0.96 ± 0.09 GJ when oriented toward the South). Still, when oriented towards the North, the magnitude of the gain is reduced (0.41 ± 0.07 GJ). Finally, while the two orientations offer similar lighting quality at low microalgae concentration, the North one decreases faster as the cell concentration increases.

Second, when comparing the office and household configuration, one can note that an office-installed biofaçade module produces more microalgae annually, mainly thanks to its larger surface area (4 m² vs. 3 m²). Finally, the illumination profile is not dependent on the type of host building.

Despite the quantity of data generated by this screening, it is complicated to identify a clear optimal microalgae concentration to operate at. Indeed, comparing HVAC burden or contribution (in GJ), produced biomass (in kg), and adequate lighting (in hours) is a matter of personal preference. Still, the HVAC contribution can be ruled out of the list of outcomes to be optimized against microalgae concentration, as in the four tested setups, it is relatively constant. Hence, the final choice is between microalgae production and indoor illumination (an indicator of occupant comfort). In order to maintain a balance between the two outcomes, it was chosen to operate at a concentration, allowing 2000 hours of adequate lighting over the year (roughly 50% of the time). This choice yielded an operating concentration of 0.75 and 0.35 g/L for the office configuration (South and North, respectively) and 0.70 and 0.25 g/L for the household configuration (South and North, respectively).

Once optimal operating concentration has been identified, it is possible to analyze performances further by comparing the biofaçade results to the ones of an equivalent double-glazing (model SunGuard™ SNX 62/27, introduced above). The comparison is graphed in Fig. 5 for the two building types and the two orientations. The first two comments are trivial: a biofaçade produces microalgae while a conventional window does not, and conventional windows allow more light to enter the host building than a biofaçade module. Diving into more interesting matters, one can note that a biofaçade module offers performance similar to that of a conventional double-glazing when heating is needed (difference of $+0.08 \pm 0.21$ GJ/year, on average over 5 years over all the configurations). The same observation stands when cooling is needed (difference of $+0.30 \pm 0.24$ GJ/year, on average over 5 years for the office configuration). It is also relevant to note that in the considered scenarii, the household does not require cooling (thanks to its flexible indoor temperature profile and location in Burlington area). Overall, it can be concluded that a biofaçade is an adequate tool to produce microalgae while maintaining similar thermal performances compared to conventional glazing.

4.1.2. Continuous mode

Fig. 6 displays the module performance as a function of the operating concentrations in continuous mode. As one can see, the trends are similar to those obtained in batch mode, yet compressed towards lower concentrations. Still, similar performance indicator values are obtained and

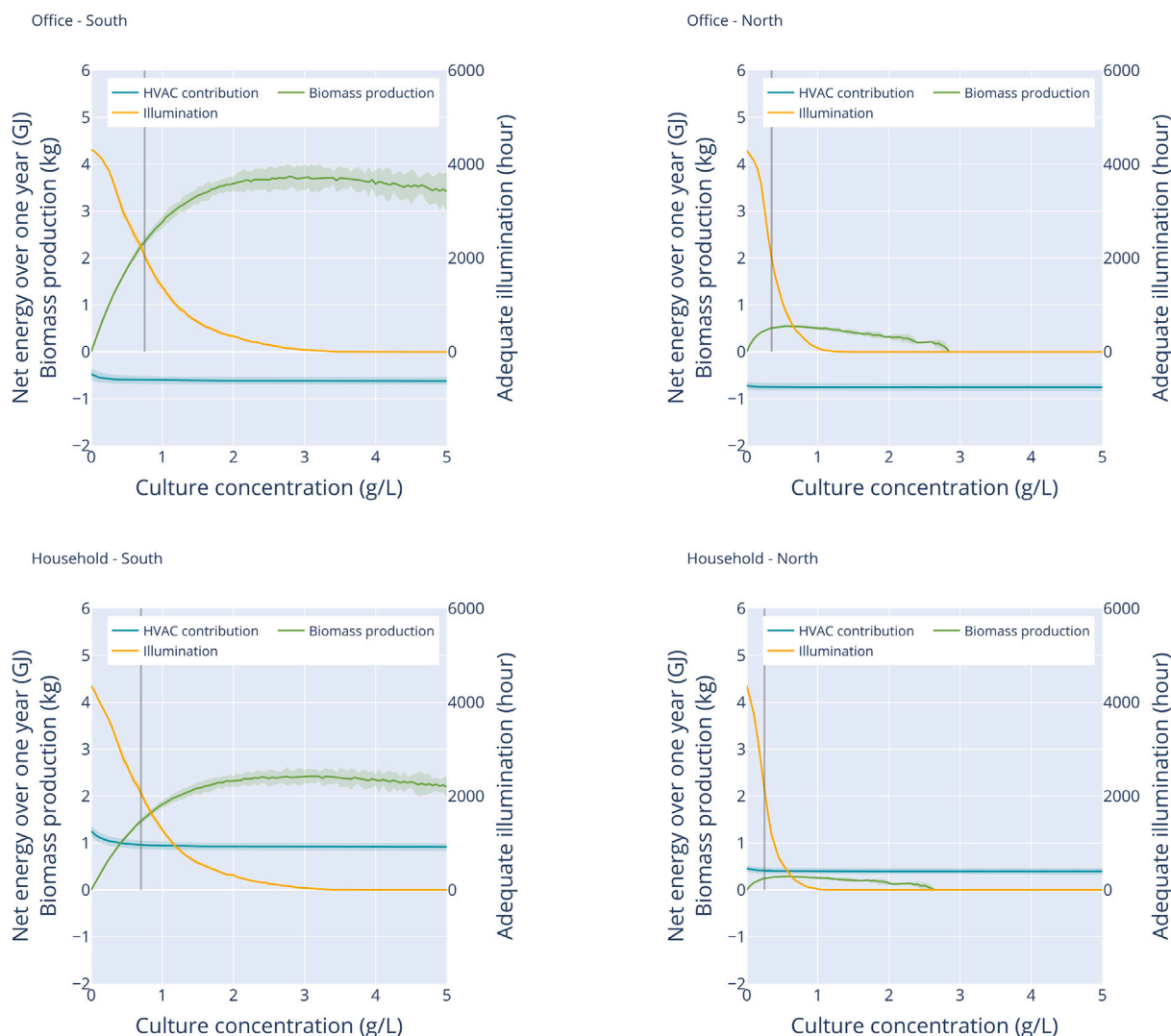


Fig. 4. Biofaçade module performance versus cell concentration, in batch mode. Top row - office building. Bottom row - household. Left column - South orientation. Right column - North orientation. Shaded areas - standard deviation obtained from the different tested years (Burlington, Vermont, from 2019 to 2023 included, $n = 5$). Vertical grey lines - operating point, defined at 2000 hours of adequate illumination per year.

batch-to-continuous differences are comprised within year-to-year variation. The optimal operating concentrations are 0.35 and 0.20 g/L for the South and North façades of the office building (vs. 0.75 and 0.35 g/L in batch mode) and 0.35 and 0.15 g/L for the South and North façades of the household (vs. 0.70 and 0.25 g/L in batch mode).

This finding is surprising as from a chemical engineering point of view, one expects that continuous operation achieves higher yields than its batch counterpart. Here, the light-limited nature of microalgae growth explains why the two modes achieve equivalent performances, with a somewhat the need for a lower concentration for the continuous mode. On the one hand, in batch mode, the cell concentration increases almost linearly (see next section). Therefore, the productivity is constant and roughly equal to the one in continuous mode. On the other hand, batch operation has a dual effect on adequate illumination. After a flush (low concentration), it widens the window for proper indoor illumination to be achieved. This translucence is then nullified once a high concentration is reached (preceding a flush). Overall, for the same amount of adequate lighting over a year (2000 hours), the batch mode allows for reaching a higher culture concentration at the moment of the harvest. Consequently, the batch mode can be deemed superior from a biotechnological point of view, as, for the same performances (biomass

production, HVAC load), it allows the harvest of more concentrated cells. Indeed, having a denser culture eases cell harvest and, therefore, reduces the cost of downstream processing [48].

Finally, taking a step back, the computed values can be compared to the ones obtained by other authors. For example, Ahmadi et al. investigated experimentally and numerically such a biofaçade integrated into a household [16]. They concluded that the optimal concentration in continuous mode was 60% of the maximal value, which corresponds to the concentration of 0.21 g/L for *Chlorella vulgaris*. Owing to the difference in setup and simulated climate, the fact that the numerical model predicts 0.35 g/L as the optimal concentration can be deemed a token of its reliability. Values of volumetric and areal productivities of Pruvost et al. (7.68 g/m²/d at about the same latitude as Burlington [18]) and Barajas Ferreira et al. (0.314 g/L/d in Colombia [19]) can also be used as check marks. Taking the office building (South-oriented) setup, based on their reports under optimal temperature conditions, one could expect to produce 11.6 and 11.2 kg/year. Still, the setup produces 2.34 ± 0.80 kg/year, which represents 20.5% of the theoretical maximum. This deviation can be explained by the gap between the actual temperature experienced by the cells during daytime and the optimal temperature. On average over a year, this leads to a metabolism efficient at $22.75 \pm$

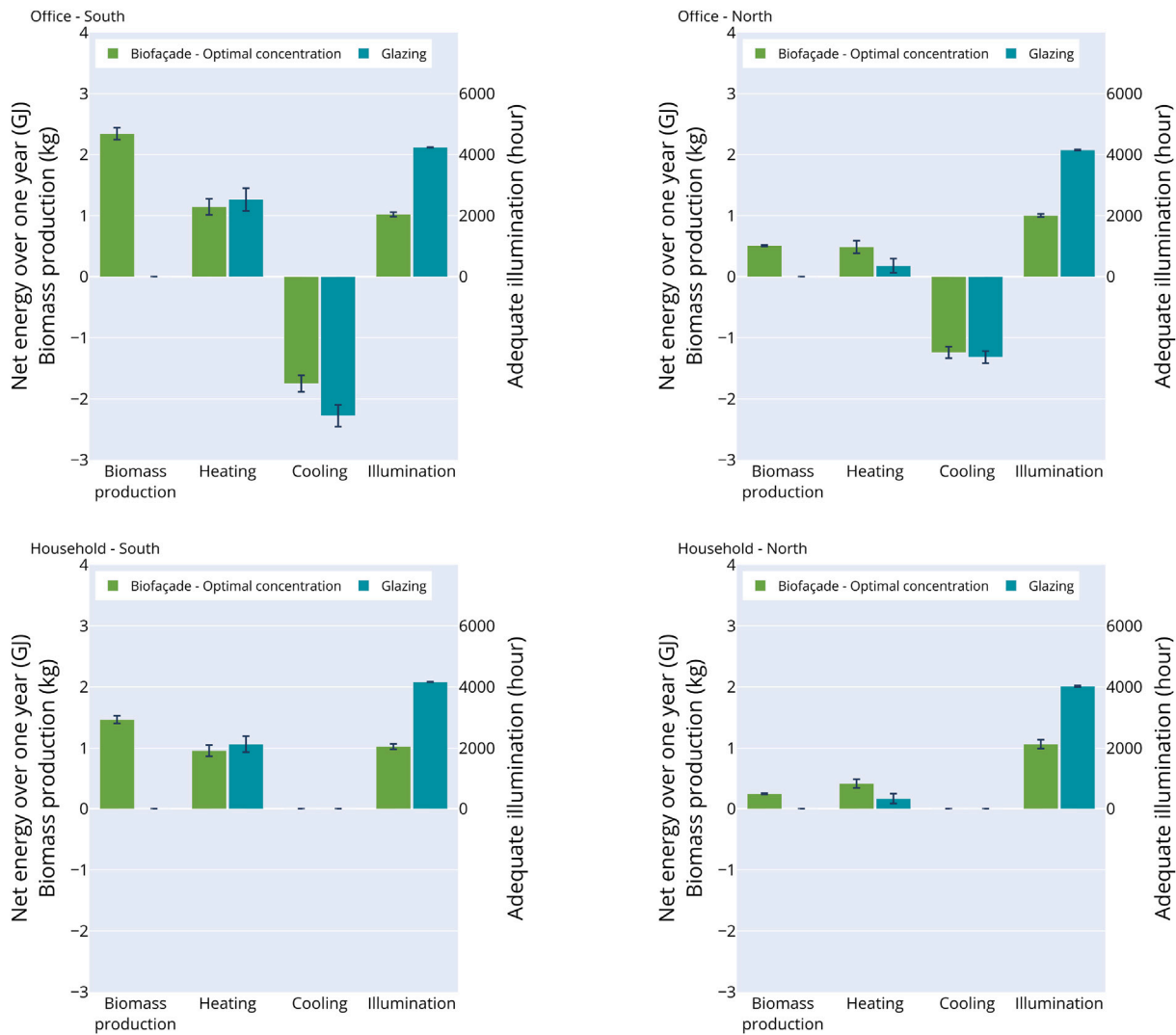


Fig. 5. Performance indicators of the different setups for their optimal operating conditions compared to a conventional double-glazing window (Burlington, Vermont, from 2019 to 2023 included, standard deviation $n = 5$).

0.50% of its nominal capacity, explaining plainly the gap between the theoretical optimum and the predicted value.

4.1.3. Culture duration & occupants' perception

With batch mode retained as optimal, it is interesting to leave annually-integrated performance indicators behind and come back to time-resolved data, as they are better suited to grasp the residents' experience in this mode of operation. The main outcome of interest is the duration of the culture. Indeed, it directly relates to the feeling of microalgae growth and system evolution that the residents will have. Fig. 7 presents the culture concentration over time, as well as the transmitted light (in log scale to mimic human perception) [49]. From a qualitative point of view, microalgae concentration increases at different rates over a year (faster in Spring & Summer and slower in Fall & Winter), and so does the transmitted light in an opposite pattern. From a quantitative point of view (Table 1), a culture lasts about 6 days in Spring & Summer and extends to 15 days in Fall & Winter for South-oriented modules (office building and household featuring close values, only one is reported). North-oriented modules reach their optimal concentration in 7 to 14 days in Spring & Summer and 31 to 34 days in Fall & Winter. All of these durations are compatible with human perceptions, neither too long nor too short. Hence, the evolution of microalgae culture can

be hypothesized to have an impact on residents' moods and feelings, as suggested by Warren et al. [50].

Finally, moving from qualitative perception of the culture growth to illumination quality indicators (Table 2), one can note that most of the difference is linked to the façade orientation, with the building type being a slight modulator only. Indeed, South orientation supporting higher cell concentrations before dilution mechanically decreases sDA by about a third of it. UDI can be used for a more detailed analysis and to explore the orientation dependence that sDA did not. Indeed, south-oriented façades offer 16.90% of the time with too-low illumination, while they are virtually non-existent for their north-oriented counterparts (1.19%). Still, adequate moments are in favor of façades facing South (51.10 versus 38.95%). Therefore, the remainder leaves north-oriented façades more prone to glaring, namely 59.88% of the time, while only 31.00% for the south-oriented ones. While it may appear counterintuitive, one has to remember that south-oriented modules support higher microalgae concentrations and, therefore, a more pronounced downward light modulation.

4.1.4. Relative humidity & occupants' comfort

Fig. 8 displays the classification of the relative humidity as Too-Low (below 20%), Below-Target (below 40%), Adequate (between 40

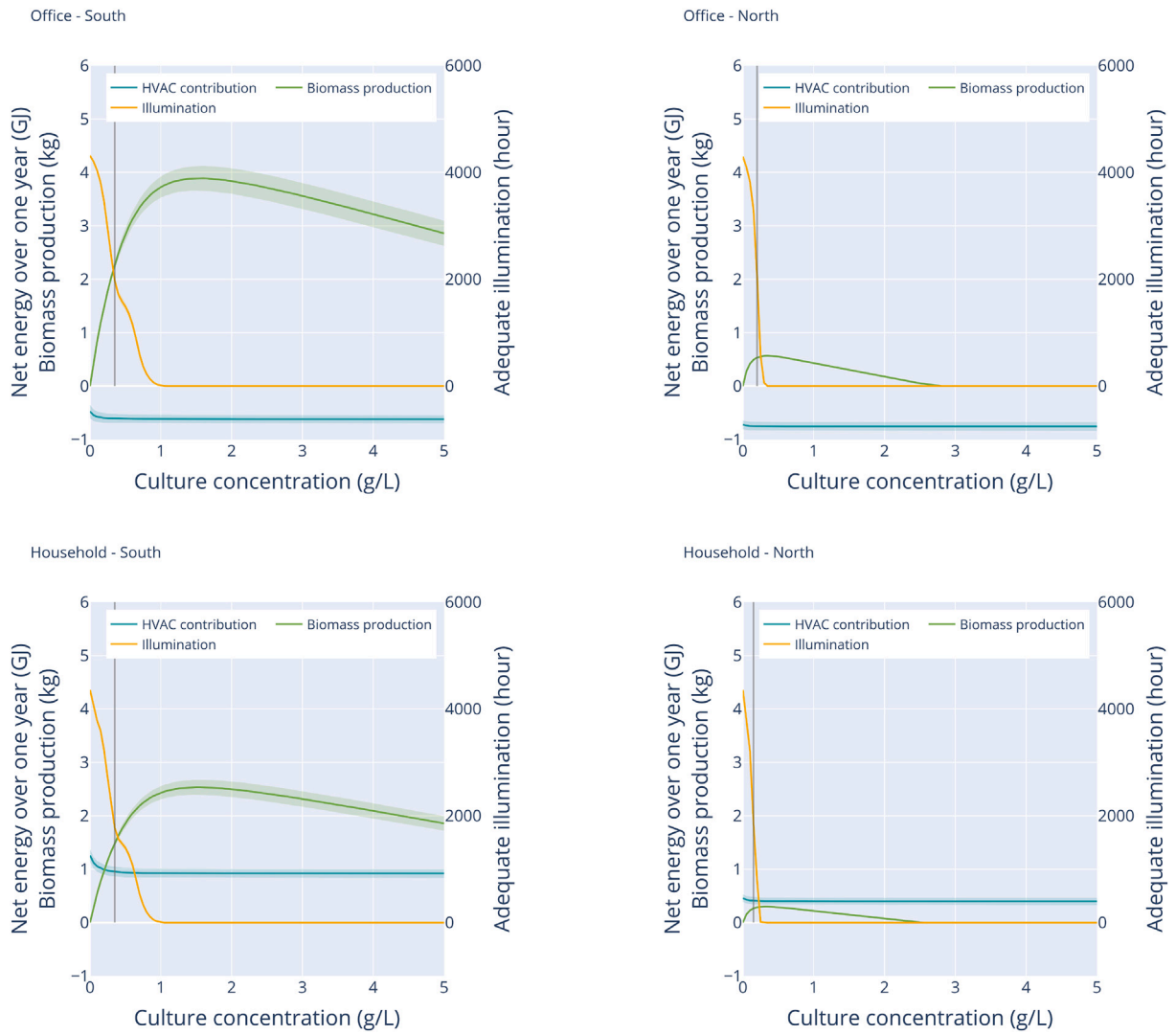


Fig. 6. Biofaçade module performance versus cell concentration, in continuous mode. Top row - office building. Bottom row - household. Left column - South orientation. Right column - North orientation. Shaded areas - standard deviation obtained from the different tested years (Burlington, Vermont, from 2019 to 2023 included, $n = 5$). Vertical grey lines - operating point.

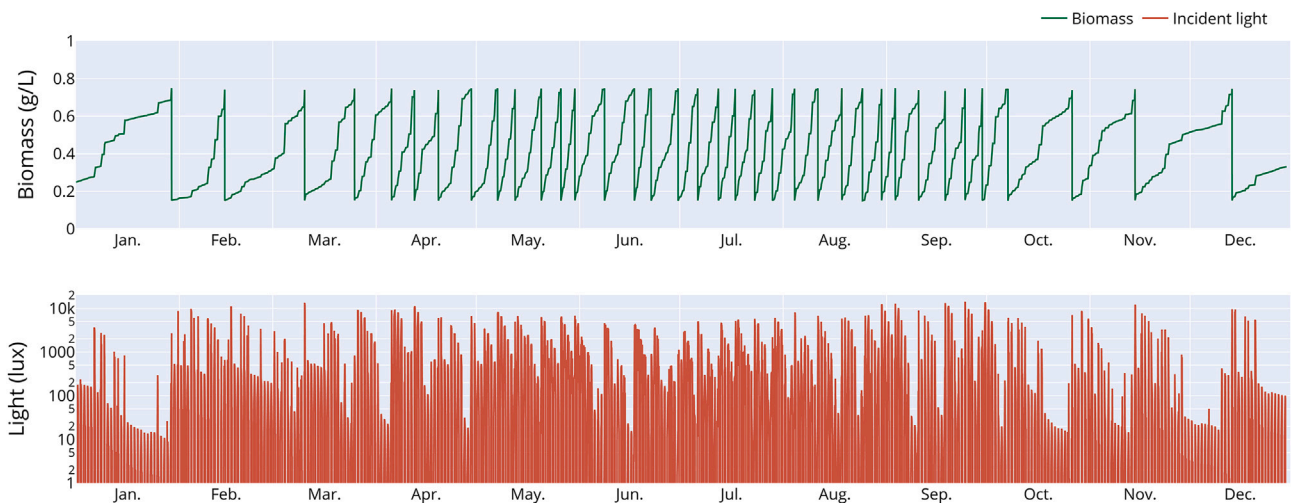


Fig. 7. Microalgae concentration (top) and transmitted light (bottom) for a biofaçade module installed in an office building (Burlington, Vermont, South-oriented, over the year 2023). Illumination graph is in log scale as human beings perceive light logarithmically.

Table 1

Culture duration and number of flushes, annually and season-wise, for the four investigated configurations (Burlington, Vermont, from 2019 to 2023 included, standard deviations $n = 5$).

	Whole year		Spring & Summer		Fall & Winter	
	Number of flush (-)	Culture duration (day)	Number of flush (-)	Culture duration (day)	Number of flush (-)	Culture duration (day)
South – Office	38.2 ± 1.6	8.69 ± 5.01	28.8 ± 0.4	6.41 ± 1.81	11.2 ± 1.6	14.04 ± 6.88
South – Household	34.2 ± 1.5	9.05 ± 6.02	27.0 ± 0.0	6.78 ± 2.10	8.4 ± 1.4	15.85 ± 9.37
North – Office	17.8 ± 0.4	17.21 ± 9.34	25.8 ± 0.4	7.15 ± 2.81	4.4 ± 0.5	30.78 ± 11.44
North – Household	16.2 ± 0.8	17.74 ± 15.83	13.4 ± 0.5	13.41 ± 3.63	2.6 ± 0.5	33.67 ± 11.22

Table 2

Indoor illumination indicators over the year 2023, Burlington, Vermont.

	Optimal concentration (g/L)	sDA (%)	UDI < 100 lux (%)	UDI 100–2000 lux (%)	UDI > 2000 lux (%)
South – Office	0.75	61.5	19.27	49.9	30.83
South – Household	0.70	60.81	14.52	54.3	31.18
North – Office	0.35	89.88	2.34	40.9	56.76
North – Household	0.25	89.22	0.03	36.99	62.99

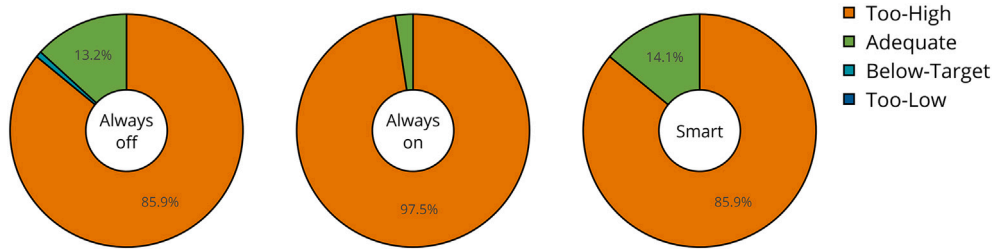


Fig. 8. Relative humidity classified as Too-Low (below 20%), Below-Target (below 40%), Adequate (between 40% and 60%) or Too-High (above 60%), Burlington, Vermont, for the year 2023.

and 60%), or Too-High (above 60%), for the year 2023, in Burlington, Vermont. The first comment is that the year 2023 was chosen for no particular reason. Indeed, all the tested years are very similar. The second comment is that Burlington local climate zone (6 A, cold-humid) naturally features a high moisture content, with the Too-Low category not being represented, the Adequate category making up to 14.1% of the year, and the rest of the time belonging to the Too-High category. This setup limits the *a priori* relevance of the use of a biofaçade module as a moisturizer. Still, a comparison between the different modes of operation is possible. Activating the Always on strategy nullifies the Too-Low and Below-Target categories compared to the Always off strategy. Still, it increases the Too-High relative humidity category substantially (+ 11.6% of the time), invalidating this strategy. The Smart strategy allows turning Below-Target moments into Adequate ones, but the gain is marginal (+ 0.9% of the time).

From this study of the Burlington, Vermont (6 A, cold-humid, climate zone) case, it can be concluded that biofaçade modules are not relevant as moisturizers. Yet, one would be right to argue that such a conclusion is location- and weather-dependent and that its generality is to be challenged. Would it be valid in a dry-cold zone? Or a dry-hot zone? Doubt commands us to lead a proper investigation before concluding. This is the topic of the next section, dealing with US-wide comparisons.

4.2. Location comparison

In order to assess biofaçade performance in contrasted environments, the same procedures were run for systems located in Orlando, Florida (2 A, climate zone, hot-humid), Missoula, Montana (6B, climate zone, cold-dry), and Phoenix, Arizona (2B, climate zone, hot-dry). As the batch mode was considered superior, only the batch mode was investigated.

4.2.1. Biotechnological & building performances

First of all, the optimal operating concentrations (*i.e.*, at least 2000 hours of adequate lighting over the year) exhibit a non-trivial

Table 3

Culture optimal concentration (defined as allowing at least 2000 hours of adequate lighting over the year) for the four investigated locations.

	Optimal microalgae concentration (g/L)			
	South		North	
	Office	Household	Office	Household
Burlington (6 A, cold-humid)	0.75	0.70	0.35	0.25
Orlando (2 A, hot-humid)	0.95	0.90	0.35	0.30
Missoula (6B, cold-dry)	0.80	0.75	0.35	0.25
Phoenix (2B, hot-dry)	1.10	1.05	0.35	0.30

pattern with respect to the location (Table 3). On the one hand, south-oriented modules exhibit higher optimal concentration (+ 33.2 ± 6.6%) when moving from a cold climate zone (Burlington and Missoula) to a hot climate zone (Orlando and Phoenix). This pattern is irrespective of building type, as both households and office buildings feature close figures. On the other hand, north-oriented modules have the exact same optimal concentration for the four tested locations.

Second, the biotechnological and building-associated performance indicators can be compared between locations and with a glazing that would be used instead of a biofaçade module (Fig. 9). For the sake of simplicity, this comparison was led for the south-oriented office building implementation case, as it features a high contrast in terms of optimal concentration (Table 3). Focusing on biomass production, cold and hot climates are also segregated, while zone humidity influences the biomass output in the hot zones only. This last observation which calls for further analysis can be explained by the difference in available illumination in Phoenix, Arizona, compared to Orlando, Florida. Indeed, examining the captured energy, a module implemented in Phoenix gathers 5.86 ± 0.19 GJ per year, while its Orlando counterpart harnessed 4.89 ± 0.11 GJ per year.

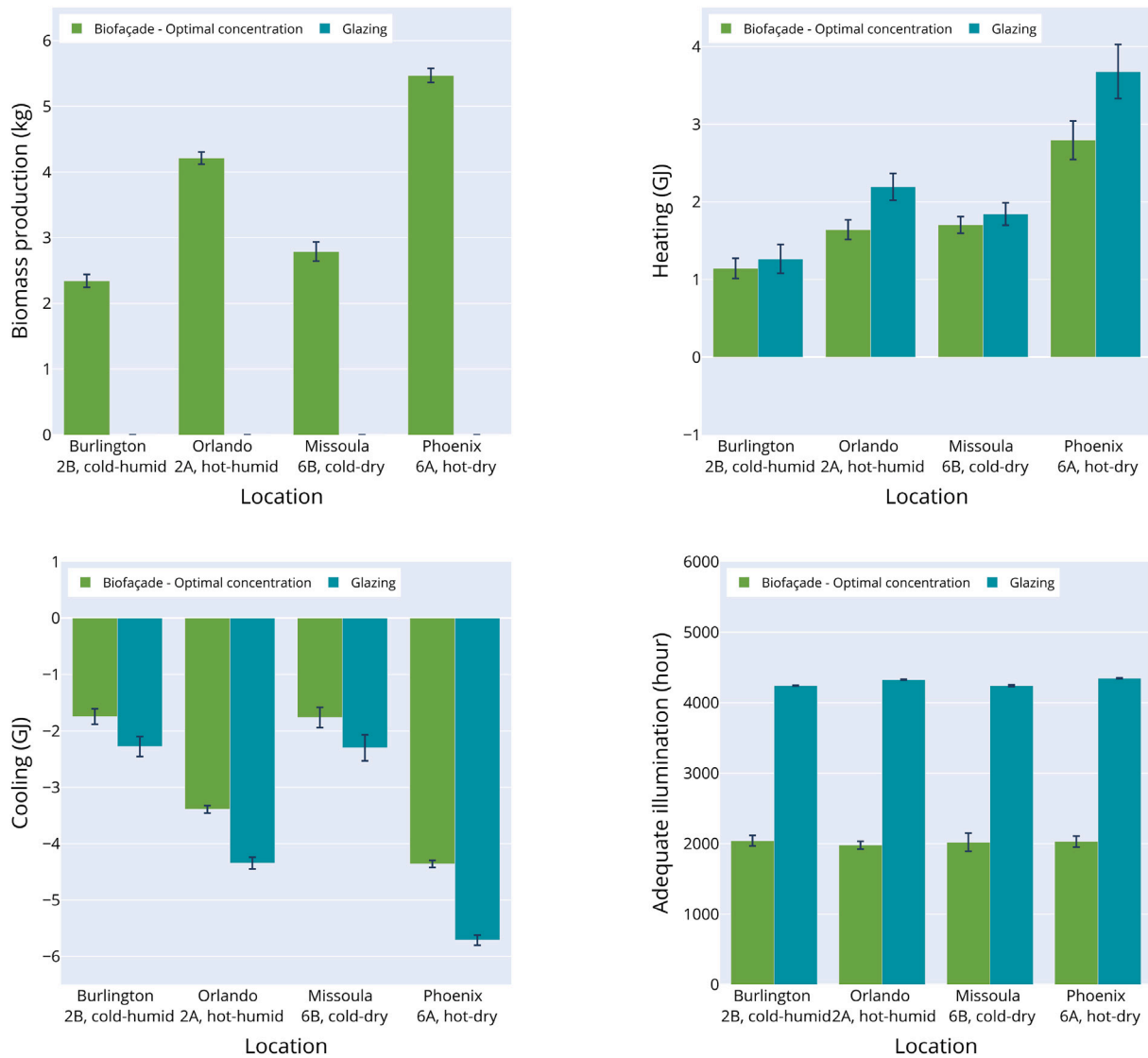


Fig. 9. Biotechnological and building-associated performance indicators for the four tested locations. Negative contribution to cooling means a burden on the building HVAC load.

Moving to heating and cooling offered to the building, the trends are the same at the four locations. On the one hand, biofaçade modules provide less efficient heating than conventional glazing. On the other hand, when cooling is required, they represent an advantage. To understand the origin of this difference, Fig. 10 presents the power balance over a biofaçade module and a low-emissivity double-glazing unit in a South facing office building on August 1st 2019 at 12 pm (building AC on). The biofaçade captures all visible light. This trait leads it to reach a high temperature and exchange more power with its surroundings, including the building indoors. On the contrary, the double-glazing only marginally absorbs incident light, as most is transmitted to the building’s interior. Consequently, its temperature is lower than that of the biofaçade module, and the resulting exchanges are of reduced intensity. Yet, it does not compensate for the direct contribution of the transmitted visible light, which ultimately drives the AC burden induced by the glazing. Overall, biofaçade and glazing both represent a burden to the building in terms of HVAC energy requirements, but with a lower impact for a biofaçade module. This gain, even though modest (0.42 ± 0.07 GJ/year/module), is consistent across climate zones and adds up to the other benefits of the operation of a biofaçade module, such

as atmospheric carbon dioxide capture, potential building wastewater treatment, or, as addressed in the next section, air moisturizing.

4.2.2. Occupant visual comfort

Moving from biotechnology and building related outcomes, the next parameter to be discussed is the illumination. First, by construction, all the modules provide 2000 h/year, when operated at their optimal concentration. Regarding the glazing, the location does not significantly influence this indicator (about 4000 h/year of adequate lighting for the four locations). More important than the total hours of illumination, the dynamics of culture proliferation are to be discussed. Indeed, it will allow building occupants to relate to the culture and have a sense of feeling it grow. Table 4 presents the average culture duration for two periods of the year (Spring & Summer and Fall & Winter) in the case of the office building. Household durations are not reported as they are quite close to office ones ($-6.0 \pm 17.0\%$ office/household pairwise difference). As one can see, the main modulators of the culture duration are the season and the orientation. In Spring & Summer a culture lasts about 7 days, when oriented towards the South, and 10 days, when oriented towards the North. In Fall & Winter a culture lasts around 6 to 14 days, when

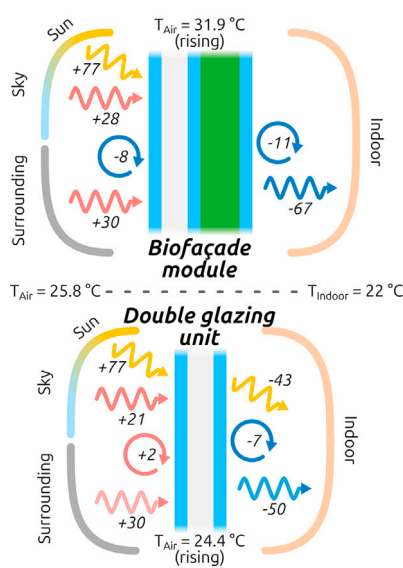


Fig. 10. Heat flux associated with a biofaçade module and a double-glazing unit, in Burlington, Vermont, on August 1st 2019 at 12 pm, when the building AC is on. Values represent heat flux intensity in W/m².

oriented towards the South, and 14 to 30 days, when oriented towards the North, for hot and dry climate zones, respectively. From this analysis, it can be concluded that in any location, microalgae cultures will grow at a pace allowing occupants to have a perception of it.

Moving to indoor illumination quality indicators, Table 5 presents the daylight performance results for the office and household scenarios for the four investigated location and the two façade orientations. The

first comment is that the building type is a very weak modulator of the results (0.12 ± 2.69 points of variation) and can be ruled out of the discussion.

Generally, cities with higher solar radiation, such as Phoenix, Arizona, and Orlando, Florida, demonstrate slightly higher values of spatial daylight autonomy. For instance, the north-facing household in Phoenix, Arizona, achieves an sDA value of 96.07%, while the same configuration in Missoula, Montana, reaches 87.71%. This difference can be attributed to the higher solar availability in lower-latitude climates, which results in greater daylight penetration into interior spaces.

The results also indicate that microalgae concentration (confounded here with orientation) significantly influences daylight availability. As the concentration of microalgae increases (south-facing), the amount of transmitted daylight through the façade decreases, leading to lower sDA values and higher percentages of insufficient daylight (UDI <100). For example, in the residential scenario of Missoula, Montana, increasing the algae concentration from 0.25 g/L to 0.75 g/L increases the proportion of insufficient daylight hours from 0.16% to 20.42% (aligned with the previous finding tied to Burlington, Vermont). On the other hand, higher microalgae concentrations reduce the proportion of excessive daylight (UDI > 2000). In high-solar climates such as Phoenix, Arizona, and Orlando, Florida, low microalgae concentrations result in a high probability of excessive illuminance near the façade, which may cause visual discomfort or glare. Increasing the biomass density helps mitigate these excessive daylight conditions by filtering incoming solar radiation.

4.2.3. Relative humidity

Fig. 11 displays the classification of the relative humidity, for the year 2023, in the four tested locations, and the three envisioned strategies. Then, the first comment is that the humid climate zones (6 A, Burlington, Vermont, and 2 A, Orlando, Florida) naturally feature high moisture content. The previous discussion drawn for Burlington applies to Orlando. Even though the potential for moisture correction is

Table 4

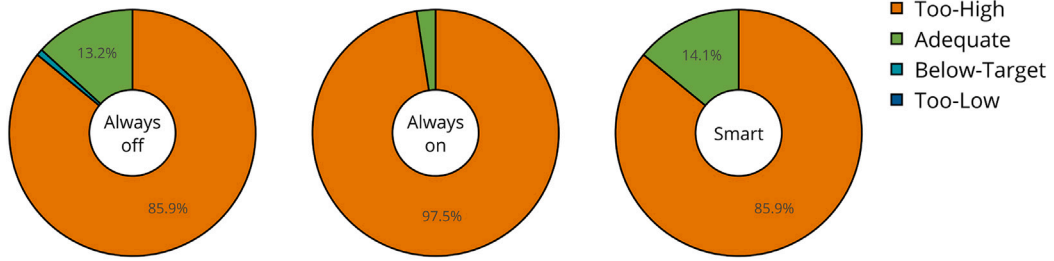
Culture duration season-wise in an office building implementation, for the four investigated location (from 2019 to 2023 included, standard deviations *n* = 5).

	Culture duration (day)			
	South		North	
	Spring & Summer	Fall & Winter	Spring & Summer	Fall & Winter
Burlington (6 A, cold-humid)	6.41 ± 1.81	14.04 ± 6.88	7.15 ± 2.81	30.78 ± 11.44
Orlando (2 A, hot-humid)	8.61 ± 2.40	5.54 ± 1.29	10.59 ± 1.72	17.90 ± 4.34
Missoula (6B, cold-dry)	6.13 ± 2.27	14.59 ± 4.14	12.90 ± 2.93	14.20 ± 9.77
Phoenix (2B, hot-dry)	6.11 ± 1.21	5.86 ± 1.10	8.85 ± 2.08	17.62 ± 5.58

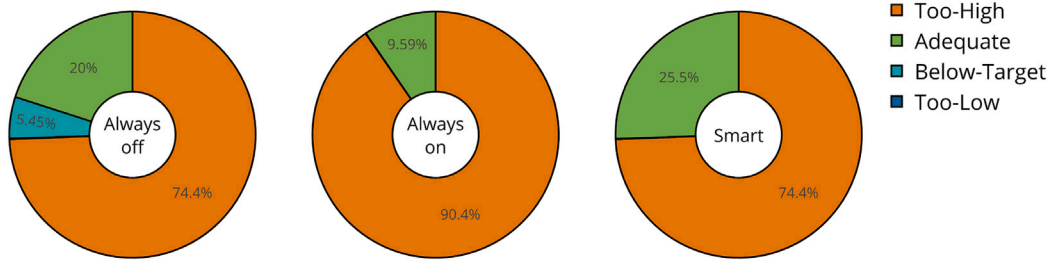
Table 5

Spatial daylight autonomy (sDA) and useful daylight illuminance (UDI) distributions for the office and household implementations, for the four investigated location over year 2023.

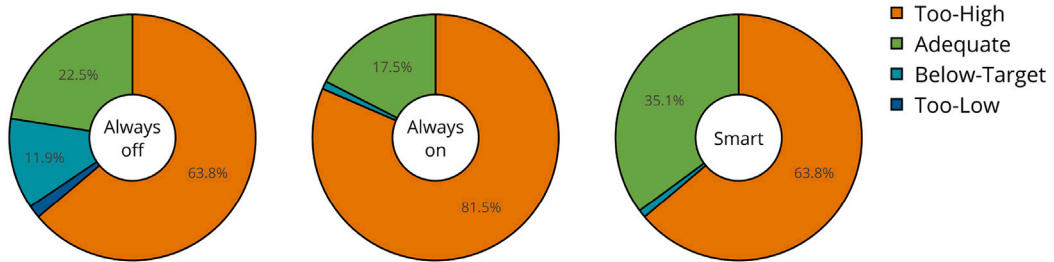
Implementation	Orientation	Location	Optimal concentration (g/L)	SDA (%)	UDI < 100 lux (%)	UDI 100–2000 lux (%)	UDI > 2000 lux (%)
Office	South	Burlington (6 A, cold-humid)	0.75	61.5	19.27	49.9	30.83
		Orlando (2 A, hot-humid)	0.95	65.53	14.98	47.57	37.46
		Missoula (6B, cold-dry)	0.80	63.43	15.85	49.15	35.00
		Phoenix (2B, hot-dry)	1.10	61.83	19.07	44.66	36.27
	North	Burlington (6 A, cold-humid)	0.35	89.88	2.34	40.90	56.76
		Orlando (2 A, hot-humid)	0.35	97.57	0.47	21.07	78.46
		Missoula (6B, cold-dry)	0.35	87.71	3.04	37.23	59.73
		Phoenix (2B, hot-dry)	0.35	96.59	0.74	15.25	84.01
House	South	Burlington (6 A, cold-humid)	0.70	60.81	14.52	54.30	31.18
		Orlando (2 A, hot-humid)	0.90	64.53	16.50	45.58	37.91
		Missoula (6B, cold-dry)	0.75	61.60	20.42	43.20	36.39
		Phoenix (2B, hot-dry)	1.05	61.84	17.61	45.90	36.49
	North	Burlington (6 A, cold-humid)	0.25	89.22	0.03	36.99	62.99
		Orlando (2 A, hot-humid)	0.30	97.52	0.04	18.73	81.23
		Missoula (6B, cold-dry)	0.25	88.75	0.16	35.50	64.34
		Phoenix (2B, hot-dry)	0.30	96.07	0.12	16.28	83.60



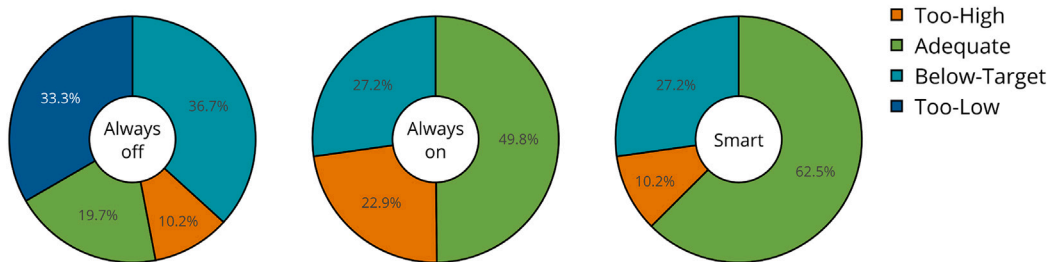
(a) Burlington, Vermont, ASHRAE 6A (cold-humid)



(b) Orlando, Florida, ASHRAE 2A (hot-humid)



(c) Missoula, Montana, ASHRAE 6B (cold-dry)



(d) Phoenix, Arizona, ASHRAE 2B (hot-dry)

Fig. 11. Relative humidity classified as Too-Low (below 20%), Below-Target (below 40%), Adequate (between 40 and 60%) or Too-High (above 60%), for the year 2023.

a bit higher (about 5% of the year), it remains too low to justify its implementation.

Still, as discussed previously, one might argue that using a biofaçade system to moist air in regions classified as humid by the ASHRAE might not be where most of the benefits can be envisioned. Missoula, Montana

(6B, cold-dry) and Phoenix, Arizona (2B, hot-dry) cities are therefore of primary interest here. Qualitatively, a system placed in the 6B region (cold-dry) delivers performances similar to the ones placed in the 6A and 2A regions. This can be explained by the fact that the reference configuration (*i.e.*, system always off) is similar in the three cases.

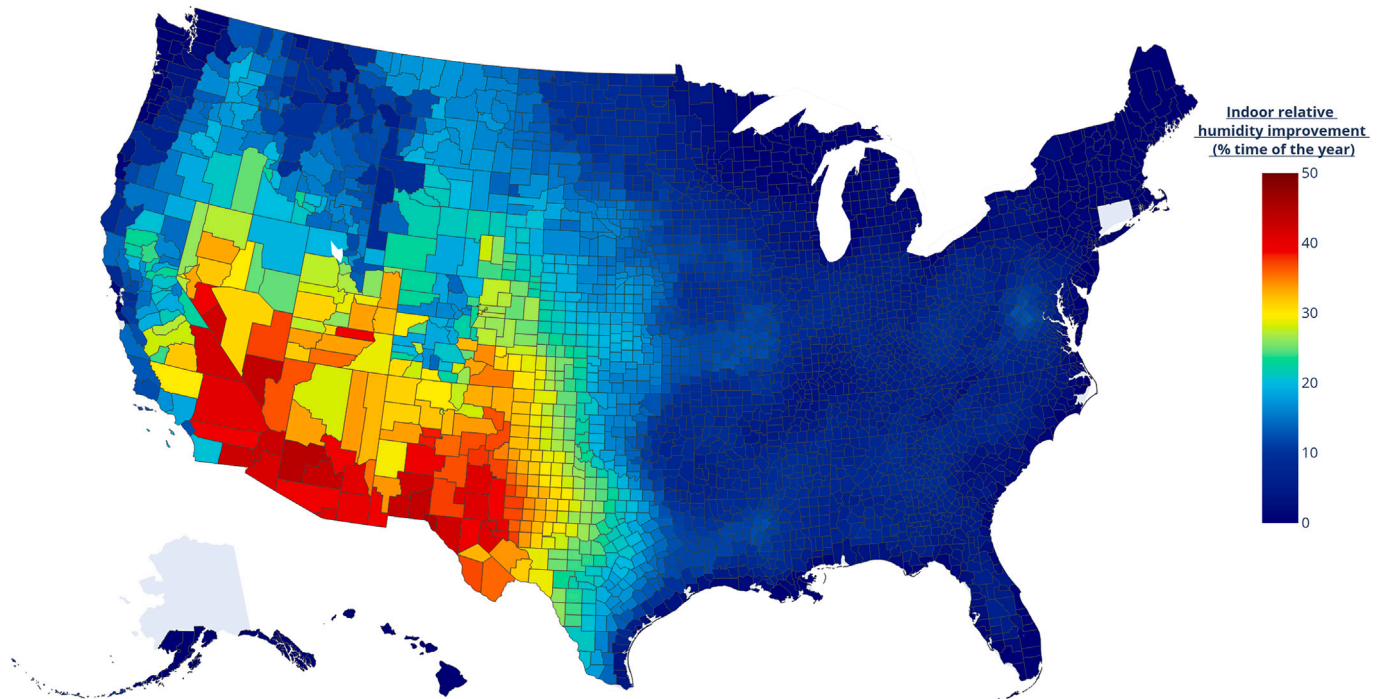


Fig. 12. Relative humidity improvement (in percent of the total operation time) over the US.

Therefore, despite minor local weather discrepancies, the outcomes are close.

On the contrary, the results show dramatic contrast in the 2B region (hot-dry). First of all, the reference configuration itself is different, featuring about 70% of the time span with Below-Target or Too-Low relative humidity. In this location, constantly venting moist air from the biofaçade modules into the room (Always on strategy) represents a sizable improvement in indoor relative humidity. Indeed, it reduces the Too-Low fraction to zero and increases the Adequate fraction from 19.7% to 49.8%, while dividing by two the Below-Target fraction. Still, it also doubles (from 10.2 to 22.9%) the Too-High fraction. Moving to the Smart operation procedure, the gains are even more interesting, with the Adequate fraction rising to 62.5% while keeping the Too-High fraction under control at 10.2%. Consequently, it can be concluded that, in a hot-dry environment, using biofaçade modules in moist air brings substantial comfort gains. Taking a step back, these analyses and conclusions align with Ahmadi et al. experimental findings [16]. Indeed, the authors reported that an algae double-glazed window increased relative humidity from about 25% to nearly 70%, in Tehran, Iran, context and suggested the appropriation of this window for dry climates.

Finally, as the location dependency appears to be non-trivial, this procedure was conducted for every county in the US. To do so, data was downloaded from the NREL at the county center coordinates for the year 2023. Fig. 12 presents the results of the analysis in terms of the improvement of indoor relative humidity provided by biofaçade modules operated using the Smart strategy. As one can see, the largest benefits (from +30 to +50% of the time) can be obtained North of the Mexican border. In addition, it is clear that the Eastern part of the US would not benefit from this option. This aligns well with the classification of ASHRAE climate zones. All in all, humid (classified A) and marine (classified C) zones would not take advantage of using biofaçade modules as a moisturizer. On the contrary, the dry zone (classified B) would, but with a clear South-North gradient, with values nearing +50% next to the Southern border, but falling at +15% or below to the Northern border.

5. Conclusion

This work compared microalgae biofaçade performance over a wide range of indicators and US climate zones. In addition, it covered office building and household implementation (showing little difference), with both South and North orientations. In terms of pure biotechnological performance, hot regions, represented by Phoenix, Arizona, and Orlando, Florida, allow for almost doubling microalgae production (from about 2.5 kg/year to 5 kg/year), compared to the cold regions (0.18 to 0.55 GJ/year), represented by Burlington, Vermont, and Missoula, Montana, when South-facing implementations are considered. From a thermal standpoint, biofaçade modules offer a slight advantage compared to conventional double-glazing in the case of an office building implementation. This difference (0.42 ± 0.07 GJ/year/module) is consistent across climate zones and is mainly driven by the summer shading effect offer by the microalgae. In terms of occupants' perception of the microalgae development, the culture duration spans from 6 to 20 days, allowing occupants to perceive it. Surprisingly, this feature is only marginally modulated by the climate zone. Diving deeper into perceived daylight, the results shows that microalgae façades can function as a passive daylight control system. While higher microalgae concentrations reduce excessive daylight and glare risk, they may also decrease useful daylight availability in climates with lower solar radiation. The results further indicate that the influence of climate conditions on daylight performance becomes more pronounced in locations with higher solar radiation. In Phoenix, Arizona, and Orlando, Florida, a larger proportion of hours falls within the excessive daylight range ($UDI > 2000$), particularly for north-facing façades where diffuse sky radiation remains high throughout the year. On the contrary, the use of biofaçade as an indoor moisturizer improving occupants' comfort shows a strong climate zone dependency. While irrelevant in hot and cold humid zones, it may be worth considering in cold-dry zones, and is very pertinent in dry-hot zones, as it drives adequate humidity moments from 19.7 to 62.5% of the time. Finally, this work calls for several perspectives that can be ranked from the most straightforward to the most demanding. From a

numerical standpoint, improved modeling of the building HVAC system and illumination (with a possible control of microalgae concentration as function of finely evaluated indoor illumination indicators, for example) could be undertaken with dedicated software. Small-scale experimental validation comes next and should confirm the HVAC gains and the biotechnological productivity. Finally, from a microbial and medical standpoint, the research verifying that using biofaçade moist air does not induce adverse effects (e.g., by releasing cells as aerosols) will have to be led before any field deployment of the system.

CRedit authorship contribution statement

Victor Pozzobon: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Ferial Ahmadi:** Writing – review & editing, Methodology, Conceptualization. **Maryam Karimi:** Writing – review & editing. **Rouzbeh Nazari:** Writing – review & editing.

Declaration of competing interest

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.

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Appendix A. Residential indoor temperature model

Residential indoor temperature was modeled empirically based on the reviews of Salthammer and Morrison [41] and Vadodaria et al. [51]. In their comprehensive literature survey, Salthammer and Morrison propose a semi-qualitative dependence of the average indoor temperature as a function of the outdoor temperature (Section 7.1.6, Fig. 12 A, for buildings in good conditions). This relationship is reproduced in Fig. 13 and modeled here by the sum of a constant and a quadratic curve (Eq. (2))

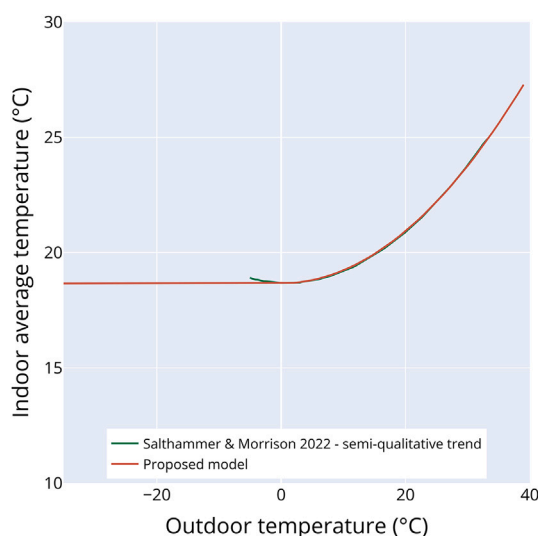


Fig. 13. Relationship between indoor average temperature and outdoor temperature. Green - Salthammer and Morrison semi-qualitative trend. Red - proposed model. Outdoor temperature range (–30 to +40 °C) chosen as the minimum and maximum outdoor temperatures encountered in Burlington, Vermont, over the 2019–2023 period.

- with the temperature in Celsius degrees).

$$T_{indoor,avg} = 18.7 + (T_{outdoor,avg} > 0^{\circ}\text{C}) \times 5.6710^{-3} T_{outdoor,avg}^2 \quad (2)$$

In addition to varying according to the outdoor temperature on a day-to-day basis, the indoor temperature also fluctuates during the day. These fluctuations were modeled by a sine function of $\pm 1.0^{\circ}\text{C}$ span around the average indoor temperature, with a minimum around 6 am and a maximum around 6 pm [41,51]:

$$T_{indoor}(t) = T_{indoor,avg} + 1.0 \times \sin\left(2\pi \frac{t - 12\text{h}}{24\text{h}}\right) \quad (3)$$

where t is the running time in hours.

Appendix B. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.buildenv.2026.114554.

Data availability

Data will be made available on request.

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