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The Potential of Co-Designing with Living Organisms: Towards a New Ecological Paradigm in Architecture

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Abstract: Living organisms have been progressively used by designers to propose alternative design outcomes aiming towards more ecological aspects. The design development and manufacturing of new materials or design components from living organisms are more achievable in textile, fashion, or product design than in architecture and construction due to the scale, multi-layer constraints, and requirements. The aim of this paper is to investigate the interdisciplinary framework, the opportunities, and limitations of introducing living organisms into the design process, including the implementation from the design ideas to prototyping until commercialization. In this paper, we focus on three types of living organisms: *algae, bacteria, and fungi*. Firstly, we overviewed and studied existing projects and experimentations to understand the design process and fabrication of living organisms in other domains in comparison to architecture. Secondly, we selected three case studies in architecture for each organism to analyze. We collected the data and conducted interviews with multidisciplinary experts involved in each case. Our findings show a better understanding of the potential to integrate living organisms in architectural design, the advantages, and the difficulties towards ecological awareness. The results from the interview and a comparative analysis show the advantages and constraints of each case. The future outlooks towards the use of living organisms as part of design in architecture are also discussed.

Keywords: algae; bacteria; mycelium; living materials; building construction; biofabrication; large-scale production; sustainability

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1. Introduction

The conventional construction industry, primarily reliant on the extraction of fossil fuels and raw materials, significantly contributes to environmental pollution and the depletion of natural resources. It is essential to cut down on energy use to address climate change and promote sustainability. This is especially important in buildings, where adopting energy-efficient practices becomes a key factor [1,2]. By lowering energy needs during construction and everyday use, we are not just reducing carbon emissions but also working towards a more sustainable and resilient future for our communities and the planet. Consequently, there has been a growing focus on fostering sustainable design production by reinforcing connections with nature, such as learning from the living or utilizing the living [3,4]. The integration of living organisms into the design process has created a novel design practice that intertwines biology and design to develop architectural solutions. By harnessing the capabilities of living organisms, such as algae, bacteria, and fungi, synergistic efforts are made to develop innovative materials and building components [5,6]. Biotechnologies are now used as a medium by artists, designers, or architects in intermediate states of artificiality, making the notion of 'living' evolve. The design resorts from now on to the 'biofabrication' to new 'disruptive technologies' of living towards the emergent field of social–ecological design [7,8].

Although the use of living organisms shows a strong potential in new design, fabrication, or new materials in different domains, there are difficulties and constraints in integrating the living as part of design and fabrication, particularly in architecture and construction. The use of living organisms has been more successfully represented in art, which is called 'BioArt'—an art practice where artists work with biology, live tissues, bacteria, living organisms, and life processes [9,10]. For instance, the artwork of Eduardo Kac involves manipulating the living, genetic engineering techniques, and genetic modification. GFP Bunny and the Natural History of the Enigma [11,12], to create a new biodiversity and a new life form, is influenced by bioscience methods and advanced technologies in synthetic biology [13,14]. Recently, artists have used living organisms or their phenomena in art to represent ecological ideas and how we react to the environment we live in and the materiality we use today. As seen in *Tangible Metric: Living Light* [15], the artist collaborated with a microbiologist [16] using art techniques to represent the biofilms phenomenon [17,18] in relation to photosensitivity from several microbes: diatom, bacteria, algae, lichen, and mosses. The artist mentioned that photosensitivity is a phenomenon at the heart of ecological issues, and the microbe biofilm formation can reflect our thoughts upon today's climate change [19].

In design, unlike art, the use of living organisms plays a role in 'functional aspects' more than 'representation'. Biodesign incorporates living organisms in the design process and production or uses living organisms as design tools [20]. The cross-fertilization of design with biology, appropriating the vital properties of organisms into materials or components, steps into another dimension of the usage with the interaction with the users. For the last decade, new strategies have been needed for more sustainable materials to improve the environmental performance of products. There are a number of alternative materials coming from biotechnology and biofabrication developed alongside [21]. 'Living textile', 'living material', and 'bio product' are in progress with a number of new research and development projects, e.g., using bacterial cellulose to grow textiles instead of producing textiles from plants [22], using mycelium to assembly waste/organic materials or grow materials [23], growing bacteria cultures on resin plates to decorate LED lamps instead of chemical pigments [24] and more (see Section 2). The notion of 'Livingness' becomes part of the design artifact framework to bring a relationship of humans with other living beings as a new social dimension [25].

The change in perspective in architecture is remarkably passing from 'clean cut concrete and hygienic look' to 'earth and dirt'. *Subnature* [26] states that *nature should be part of architecture, and also architecture should be part of nature*. Today, the integration of nature as a 'living architecture'—in most cases—still relates to the use of plants or trees for vegetative façade, roofs, or components [27–30]. The integration of other types of living organisms or microorganisms is progressing among research groups at the early design stage, still rarely seen in architectural commercialization.

The increasing use of living organisms in architecture at present derives from the main shift in the new order industry revolution, from mechanized production to biologically driven processes. The metabolic thinking in the circular building industry is driving ideas of new urban ecology, design circulation, and biodegradable materials so that architects gain more and more interest in using living organisms to cultivate building materials and productions. The new age in the design and engineering of living things offers new ecological models of the built environment [31–33].

Although the use of living organisms shows a number of positive potentials towards a more sustainable built environment, in architecture, there are multi-layer requirements to fulfill according to building standards and regulations, which limits the further implementation of living organisms in design production. Moreover, the use of living organisms as part of design is not yet familiar among traditional building specialists. The integration of living organisms in architectural components or building materials design is still in the preliminary stage, as there are main gaps in the theoretical research level in laboratories and real-world applications [5].

The aim of this paper is to better understand the complexity and interdisciplinarity of co-designing with living organisms and its potential wider application in the architecture domain. We focus on the three most utilized types: algae, bacteria, and fungi. Firstly, we make an overview of the major characteristics of each organism in relation to their vital properties used in different domains. Then, we focus on design and architecture. Secondly, we select three main case studies: *algae façade, bioluminescent for architectural passive light, and mycelium exterior panels* for study and analysis in terms of initial design ideas, development, fabrication until final production, including the challenge of ecological awareness along with the integration of living organisms in architectural design and construction. We conduct interviews with involved multidisciplinary experts and architects of each case to understand different perspectives from different disciplines. We use the same questions set for a semi-structured interview. Finally, the authors demonstrate the findings in the form of comparative data analysis and propose future outlooks that can be further progressed in this young domain. Accordingly, the article is organized into five sections: (1) introduction; (2) living organisms as part of designs; (3) materials and methods; (4) analyses and results; (5) discussion; and (6) conclusion and future visions.

2. Living Organisms as Part of Designs

The kingdom *Plantae* is widely used as part of designs rather than *Animalia*, mainly because plants have interesting, vital properties to new design challenges in relation to ecological aspects, e.g., photosynthesis to produce energy [34–36]. For the last two decades, there have been a number of projects that use plants integrated in architecture and construction, particularly green façade or roof system design [37–40]. Plants and trees are more widely known to architects rather than other living organisms.

Microorganisms like mushrooms, algae, bacteria, or yeast are long known for their use in alimentary and pharmaceutical industries [41–43] rather than in design. But at present, their uses are progressively expanding to other fields. There are a number of new design and material creations that integrate different biological organisms, e.g., mushroom mycelium, laminaria algae, bacteria, yeast, etc., to generate new durable and biodegradable objects.

Bioengineered fashion is beginning to make new, more sustainable materials grown in labs and made with microbes. Designers have also started to use yeast and bacteria to grow cloth fabrics. There are a number of ongoing research and developments, such as bacteria growing into a fibrous mat of "bio-leather" or drying organic silk dyed with bacteria [44,45]. In [46], it is shown that the use of *Gluconacetobacter* produces a cellulose-based biofilm, and it is this, plus various yeasts that may also be growing in it, which have been used to produce paper and fabric-like material. Contemporary designers use algae to produce bioplastics to replace polyester to create a petroleum-free dress [47]. Mushroom mycelial growth also contributes to the production of bioplastics, packaging, foams, and production of fully degradable wearable components—to replace conventional materials, like leather, inputs with biodegradable footwear, e.g., Mushroom® Packaging and Mycelium shoe soles [48–53].

In design and architecture, as referred, the use of plants is still widely known as part of façade components or what we call 'green walls', which can be beneficial to improve air quality in urban environment [54]—as plants produce oxygen—and also to reduce heat [55]. Recent projects show new designs with trees along with advanced technologies. For example, *Baubotanik*, by Ferdinand Ludwig, University of Stuttgart, is an architectural system that uses trees as a load-bearing material and transforms them into natural walls. This project is dedicated to designing trees as visionary concepts for a new green architecture. It shows the possibilities of such living constructions and that architecture becomes part of urban nature [29]. Another interesting example of creating 'architecture as an ecosystem' is the Primary School for Sciences and Biodiversity, Boulogne-Billancourt, in

2014 by French architect ChartierDalix. The entire envelope of the building is designed to be able to host flora and fauna so that nature is a part of the long-term living design of the situated building in its local biodiversity (Figure 1) [30].

(**a**) (**b**)

Figure 1. (**a**) The concept of 'living envelope' composed of three layers: structure/insulation, nutrition, hosting fauna, and flora. (**b**) The living envelope is implemented at the Primary School for Sciences and Biodiversity, Boulogne-Billancourt. Images: (**a**) ChatierDalix architects, (**b**) Natasha Heil.

Today, there are a number of possible applications and benefits from the use of living organisms in the architecture domain. Some of today's challenges and benefits are thermal insulation, air quality, low energy production, low carbon footprint, low maintenance, and circularity [56]. The use of plants and trees is more well-known than other living organisms—in particular—microorganisms.

Microbiology, biotechnology, and computation become part of new approaches to next-generation sustainable design [57], but the use of microbes as part of building components or materials is at present still in the fundamental research stage [58,59].

The traditionally passive role of architects is changing; rather than only selecting materials as a finished product, they are taking part in designing new materials in a bottom-up manner to respond better to challenged performances. Material scientists alone cannot propose a specification of a new material type to match building-specific multi-requirements [5–60].

Engineered living materials (ELM) are new forms of materials that can grow, sense, and adapt similarly to biological organisms [61]. ELMs are still a young field developed within laboratory research groups (mainly material scientists). Most of the research and development projects are preliminary stage prototypes and at very small scales [62,63]. The main applications of ELMs are material production, smart surfaces, and tissue engineering [64]. The field of engineered living materials is still state-of-the-art for architecture and construction [65]. Among architects and building specialists, the integration of living organisms as part of building materials must enter into a circular building industry, not only a material performance alone. Cultivating living organisms can be a novel resource for the building industry and can offer a new circularity, changing from a linear to a close-loop system [31,66,67].

We will make an overview of the main organisms used in design, which are fungi (mycelium), algae, and bacteria, according to their interesting, vital properties to fulfill new building material multi-functional designs and performances and discuss some details of interesting examples in the following subsections.

2.1. Fungal Mycelium

The fungi kingdom, closer to animals than plants, spans multiple scales up to macro biology. Mycelium (plural mycelia) is the vegetative part of a fungus, which is, for instance, subterranean, under a mushroom (i.e., its fruiting body), consisting of a network of fine filaments (hyphae) (Figure 2). Fungi are widely used in our industry. Paul Stamets presented a circular model in which fungi are used to produce food, medicine, and fertilizers while decontaminating soils [68]. In recent decades, fungal mycelium has gained popularity as a sustainable alternative to various materials typologies developed today [69]. The production of mycelium-based materials could be added to this circular model, manufactured in parallel to the production of food and medicine, which focuses on the fruiting bodies [70]. There are two main types of mycelium-based materials: pure mycelium materials (PMM), mostly applied in the fashion industry for their leather-like material properties [71], and mycelium-bound composites (MBC), mostly for packaging, product, and building insulation (e.g., foam-like material), due to their increased rigidity from the added substrate.

(**a**) (**b**) (**c**)

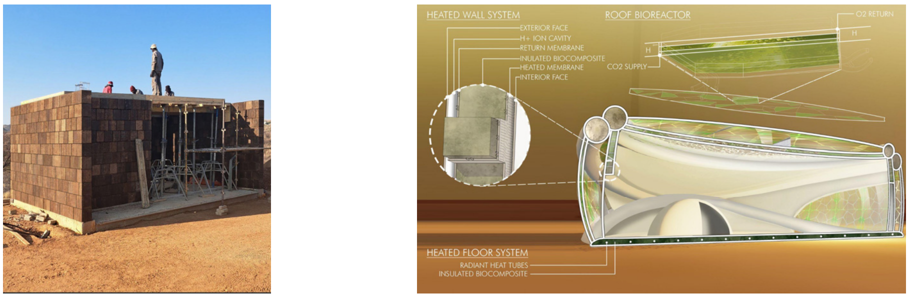
Figure 2. Stages of mycelium growth over the substrate: fungal mycelium starts to develop from the inoculated spawn mixed with the pasteurized substrate; (**a**) over time, (**b**) it colonizes the substrate, (**c**) until it covers it entirely with its network of hyphae. Image: Thibaut Houette.

Mycelium-bound composites are manufactured by growing a mycelium-forming fungus on an organic substrate. As the mycelium feeds on the substrate, it binds substrate pieces through a network of filaments (i.e., hyphae), resulting in the formation of a porous material [72–74]. Various variables (e.g., fungal species, substrate chemistry and morphology, growth environment, and post-growth treatments) serve to fine-tune material properties [75–83] and target a wide range of applications, including packaging, thermal insulation, acoustic absorbers, electronics, footwear, fire protection, and self-healing materials [49,84–91] Throughout the design and manufacturing process, each decision has to be taken with both biological and architectural point of views, knowing that most variables affect each other leading to very complex design, manufacturing, and research processes [92,93].

Mycelium composites are seen as one of the most successful large-scale engineered living materials (ELM) [63,70,79,94] thanks to the variety of applications, including the successful commercialization of designed products and packaging materials and the numerous patents developed [48,73]. Despite their success in the design field, many questions are yet to be answered before their implementation into the building industry [69,70,95]. For instance, material properties are highly heterogeneous as they depend on substrate arrangement and growth of a living organism. Beyond ensuring suitable material properties, the ecological and health impacts of implementing mycelium materials on a large scale should also be researched. Applied research on mycelium-based materials' potentials goes in tandem with fundamental research on understanding the fungal diversity of species and respective growth and properties. Therefore, building with living systems not fully understood and characterized requires many explorations, which could be seen as unproductive and, in response, constantly affect the Technological Readiness Levels (TRL) in a non-linear and traditional way [96].

Mycelium has also been grown inside 3D printed to grow complex material shapes and on tensile scaffolds to solidify flexible morphologies [4,97,98]. In the FUNGAR project or Living Room fungus project, mycelium is respectively grown over a sparse Kagome weave pattern or knitted wool, which serves as a stay-in-place scaffold [99,100]. The Pulp Faction project demonstrates both the challenges and the potential of additive fabrication of mycelium composites [93]. While MBC grown in frames are easier to mass produce and maintain in sterile environments, 3D bioprinting them allows for morphological complexity, which can serve to generate a high surface area to volume ratio in order to increase airflow, resulting in higher oxygen access, enhancing growth, more homogeneous moisture, air, and heat levels, and fasten even desiccation. The *transcalar* production of MBC through 3D bioprinting crosses the nano (i.e., chemical transformations), micro (i.e., hyphae network), milli (i.e., substrate composition and extrusion process), meso (i.e., printed components), and macro (i.e., assembly of parts into a large, designed structure) scales [92]. In addition to the interconnectedness of variables previously discussed, the scales at which the material is designed are also interdependent. Beyond human habitats, mycelium-based materials have also been grown on 3D-printed clay or polyvinyl alcohol (PVA) scaffolds to produce therapeutic habitats for honeybees through the HIVEOPOLIS project [101]. The introduction of fungus improves the properties of the resulting material in multiple ways, resolving difficulties associated with wood printing through improved water resistance and increased stiffness and hardness. (Imhof & Gruber, 2016 [4]; Goidea et al., 2020 [93]; Goidea et al., 2022 [92]). In an aim to understand, predict, and influence the morphology of growing mushrooms, the effect of environmental factors on their growth pattern has been studied to understand their potential parametric behavior [102]. Most temporary installations serve as demonstrators of the material's properties and potential, while the research is performed inside laboratories at a small scale.

In an effort to tune this fabrication process to construction scenarios and increase production scale outside of a microbiology laboratory, Redhouse Studio started the Bio-HAB project in Namibia in 2019 (renamed MycoHAB in 2022), where they grow building materials while cleaning the ecosystem from invasive species and producing food with local communities [103]. This firm has also worked on manufacturing panels at a larger scale outside a laboratory setting, in partnership with The University of Akron, on a project in which the produced materials were tested for their outdoor durability (Houette et al., 2020 [80]). This architectural firm is also exploring the growth of mycelium materials for outer-space architecture integrated into the life cycle of the astronauts and their habitat in extreme environments [104]. Using mycelium to fabricate outer-space architecture at a destination is highly interesting as it considerably reduces the mass and volume of materials (i.e., mycelium strains) transported from Earth, which will be grown on local waste products (i.e., astronauts' or bioreactors' by-products) (Figure 3). Due to the challenges associated with outer-space habitat, multiple functions of fungi can be integrated throughout the life cycle of mycelium-based materials and further enhanced through bio-engineering and associations with other life forms [104]. Such functions include waste processing through their natural enzyme secretion for food uptake, radiation protection, self-healing, humidity regulation, energy, light and nutrient production, ventilation, and psychological comfort. However, growing living organisms requires resources such as water and oxygen, which are difficult to collect outside of Earth, need to fall under strict regulations, could be impacted by unprecedented situations on location, could be at risk of forward and backward contamination and of generating biodegradable materials with a limited lifespan of approximately 20 years. Going further, the electronic properties of fungi are also researched to develop living mycelium-based electronic devices embedding sensorial and computing circuits [105,106]. In conclusion, the fabrication of materials from fungal mycelium has already shown many promises for the building industry thanks to the diversity of variables to tune their characteristics and functions to specific applications, but it still requires further research and exploration before they are implemented in permanent buildings.

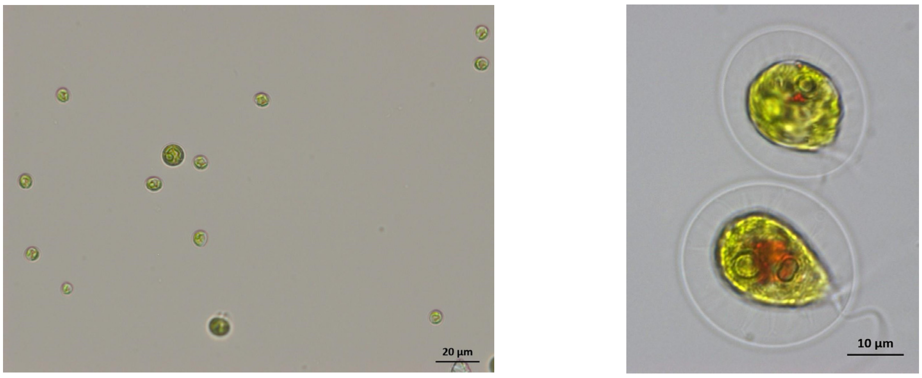


(**a**) (**b**)

Figure 3. (**a**) Redhouse Studio architectural projects with materials grown from mycelium cleaning the ecosystem while producing food, (**b**) and integrated into the astronaut's life cycle in outer space. Images: Redhouse Studio.

2.2. Algae

The term algae refers to macroalgae and microalgae. Members of microalgae are mostly photosynthetic, and they live in the marine environment, where they are the primary producers of oxygen and valuable organic compounds [107]. Figure 4 shows an example of two microalgae species: *Chlorella vulgaris*, used widely for photobioreactor cultivation, and *Hematococcus*, known as the richest source of natural carotenoid called astaxanthin, used widely in pharmaceutical industries.

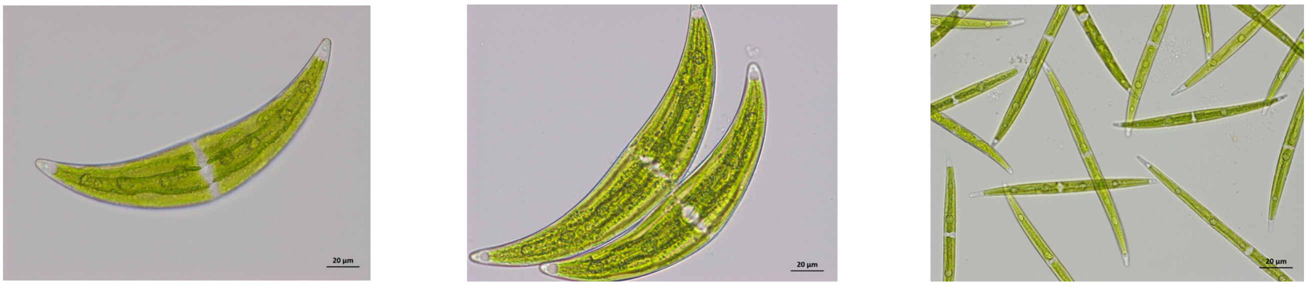


(**a**) (**b**)

Figure 4. (**a**) *Chlorella vulgaris*, (**b**) *Haematococcus pluvialis*, microscopic images taken and courtesy by Sahima Hamlaoui at Molecules for Communication and Adaptation in Microorganisms (MCAM) Laboratory of National Museum of Natural History of Paris, France, 2023.

Microalgae have been cultivated for years due to their wide range of usage; the cell can be cultivated faster with correct nutrition and in favorable environmental conditions (temperature, etc.) (Figure 5). In the textile industry, algae fabric and natural dye [108] are used; in the health industry, microalgae are used in biomedicines and mobile microrobots, from tissue engineering to tumor therapy [109]. Even in cosmetic products, microalgae are used [110]. In the food industry, they are considered for food supply, food additives, or alternative fish meal [111–114]. In order to point out the nutritious nature of microalgae, Aleksander Wadas Studio designed an architectural pavilion with a closed-loop photobioreactor that produces microalgae biomass. The pavilion *Algae Dome* was installed at the Copenhagen Chart Art Fair in 2017 and gave visitors the opportunity to taste spirulina chips produced from the algal biomass. Since microalgae have minerals, vitamins, and iron that are higher than in spinach and protein more than twice as much as meat, the installation gathered attention [115,116]. Moreover, algal biomass is an eco-friendly alternative for bio-fertilizers and a sustainable option for wastewater treatment [117,118]. In addition, microalgae have an important place in electricity, biofuel, and biogas production [119].

The studies show that microalgae are getting attention and becoming an alternative in various fields.



(**a**) (**b**) (**c**)

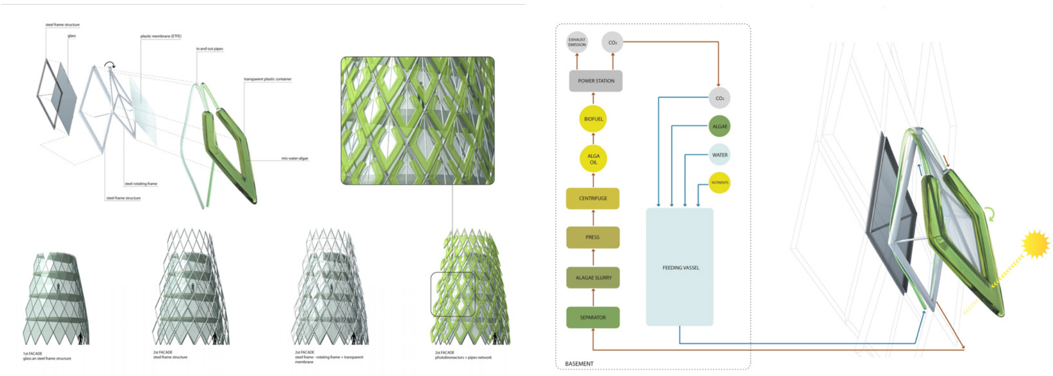
Figure 5. (**a**–**c**) An example of microalgae (*Closterium* sp.) reproduction from one cell to multiple cells, microscopic images taken and courtesy by Sahima Hamlaoui at Molecules for Communication and Adaptation in Microorganisms (MCAM) Laboratory of National Museum of Natural History of Paris, France, 2023.

The use of microalgae in architecture brings many benefits. These benefits can be exemplified as energy saving, reducing CO_2 emissions, oxygen generation, biofuel production, and wastewater treatment from the micro-level through building façade implementations to the macro-level through urban scale integrations [120]. There are several conceptual ideas of architectural algae provided by 'ecoLogicStudio', an architecture and design innovation firm specializing in biotechnology for the built environment [121–125]. Many of their projects explore the use of microalgae for purifying air in urban environments, bioenergy generation, and architectural photosynthesis. Notably, *Air Bubble* is an indoor playground for children that provides purified, clean air with microalgae photobioreactors. Located in the center of Warsaw, Poland, the *Air Bubble* has 52 bioreactors containing approximately 520 L of living *Chlorella* in the ETFE membranes. It has a cylindrical timber structure and an inverse conical roof that allows air circulation inside. With the sensors, indoor air quality is monitored throughout the year. Moreover, their most recent project is *Air Office*, which is an indoor bio-garden that is installed in an office building located in Nyon, Switzerland. This garden hosts 12 microalgae photobioreactors, each filled with 10 L of liquid. Photobioreactors are carried with 5×8 m wood structures. The space creates clean air in the workspace and provides interaction with nature for a relaxed working environment [125].

As we can see, microalgae have different contexts in design with a variety of scales. From installations to urban scale, architects are considering microalgae as a design element, some of which have multiple purposes. In addition to the purification of air for indoor air quality, CO_2 reduction, and biomass production, microalgae are also beneficial for the creation of relaxed environments.

Building façade is an important design element to save energy. Façade integrated microalgae photobioreactors for building energy efficiency are in progress. Since they are opaque systems, microalgae bio-facades can decrease the heating and cooling demands of the building and improve the overall energy efficiency of the building. The photobioreactor systems on the facade can reduce energy consumption by up to 50% and provide thermal insulation [126–128]. Buildings can gather required heat and electricity from microalgae, and this technology can serve as an alternative system. Moreover, it can be a carbon-neutral power source and can help with GHG mitigation [129]. However, the cost of cultivation of microalgae in photobioreactors on the ground is still less expensive than the cultivation on the building façade [130]. One of the successful, well-known cases is BIQ Building by ARUP. It was first constructed in 2013 with the integration of microalgae photobioreactors to its façade, located in Hamburg, Germany [131].

In addition, two research experimental cases come from architecture studios showing the integration of microalgae in large-scale façade design. One is *Algae Tower*, a photobioreactor façade conceptualized by UOOU studio, located in Melbourne, Australia (Figure 6). The research focuses on biomass and energy production through several microorganisms with photobioreactor design. The façade elements are adjustable to the optimum sun angle for photosynthesis to maximize the biomass amount and effectiveness of the shading in summer [132].



(**a**) (**b**)

Figure 6. Algae tower: (**a**,**b**) concepts of photobioreactor façade. Image credit: UOOU Studio (Como, Italy).

Another example is *Algae-Covered Towers* from French studio XTU Architects (Paris, France). The architects have developed a concept for four twisting glass towers with an organic facade that produces oxygen, absorbs CO_2, and provides valuable proteins with edible *Spirulina*. The featuring façades are covered in panels impregnated with microalgae. The algae-covered tower is located in Hangzhou, China [133,134].

However, the applications of microalgae are more widely applied in biomass, biofuels, and bioproducts; on the other hand, in an architectural context, it is relatively new. However, there is progressively ongoing research and development of microalgae cultivation and photobioreactor design for the future outlook of the architecture [135,136]. In the photobioreactor design, various parameters are considered, including species, light amount and light angle, O_2 and CO_2 supply, temperature, pH, mixing strategy, and flow regime. Keeping the environmental conditions optimum for culture growth, high cost of production, power consumption for the system's maintenance, and complexity of system expansion for mass production are still the challenges of the photobioreactor application [137]. For that reason, the achievements in the photobioreactor systems will depend on the cost and payoff balance for applications. In addition, an integrated design approach is needed for photobioreactors to become an effective building system. There are various concepts at the design stage but only a few real-life applications, which show the infancy of the technology [129].

As discussed before, there is one specific group in microalgae: *Dinoflagellates*, bioluminescent ones, which have gathered attention only recently due to their biological light production. Bioluminescent organisms are very common in the marine environment as there are many bioluminescent organisms, such as bacteria, microalgae, coelenterates, beetles, and fishes [138]. However, in terms of abundance, *dinoflagellates* and bioluminescent bacteria dominate the light emitters [138]. Bioluminescent dinoflagellates have been used as a reporter for toxic materials, biological sensors, and biomedical research [139]. Although they have been used in other fields, their architectural usage is relatively new. One of the rare examples is *The Bio-Light*. The prototype uses bioluminescent microalgae *Pyrocystis fusiformis* to create biological light. It takes up to 15 L of bioluminescent media, and with the help of gravity, it can glow for up to 20 min. It is a natural renewable light prototype [140].

Since light is necessary for humans to visualize the environment, it is also important for building interiors. There are many lighting sources developed over the years for interior usage. Here, a question arises: can bioluminescent light be used in the building interiors in addition to traditional lighting sources? Abundancy, rapid growth rate, being mostly autotrophic, and having high light intensities can make bioluminescent dinoflagellates a potential for interior usage, maybe even better than bacteria [138,141–143]. To investigate the question, research presents the usability of bioluminescence in building interiors (Demirci, 2022). Bioluminescent algae have the potential to be used as a light source in the built environment. Implementation of the bioluminescence feature of microalgae in architecture is relatively new. To investigate this potential, there is a prototype idea that employs bioluminescent algae *Pyrocystis fusiformis* with photobioreactors for interior lighting. According to the research, bioluminescent light can compensate for traditional interior lighting when existing lighting is not enough. In addition, it can be used independently where we do not need so much light, such as entrances and corridors. In Figure 7, the simulation of the bioluminescent lighting integrated condition of the selected flat's closed balcony can be seen. In this area, before the implementation, average illumination was 42.5 lux. After 1 L of bioluminescent media, the average illumination has arrived at 103 lux [144].

Figure 7. Rendered image from the simulation of bioluminescent lighting in the closed balcony area, Image: Özge Demirci.

2.3. Bacteria

Bacteria were unicellular microorganisms that were the first forms of life to appear on Earth. Bacteria are widely used in the food and health industry, such as Lactobacillus and Bifidobacterium contained in yogurt [145]. Recently, there has been progress in the use of bacteria in the textile industry to develop a biomaterial from bacteria that can be used to create a low-carbon alternative to traditional clothing in various contexts [146]. Kombucha Bacterial Cellulose is also progressively used in many other domains of industrial production and applications; it is considered a highly versatile green material with tremendous potential [147,148]. Despite the positive potential of these biodegradable materials from bacterial microbes, there are some constraints to overcome towards a full-quality clothing fabric for manufacturing, commercialization, and real usage (e.g., need an optimal temperature for the growth, non-water resistance, etc.).

In architecture and construction, different types of bacteria have been used for different building materials and processes according to their vital properties, for example, for heat, electricity, repair, material growth, cementation, etc. Self-healing concrete (also known as Bioconcrete) was initially developed by Henk Jonkers at the Technology University of Delft, utilizing *Sporosarcina pasteurii* (*Bacillus pasteurii*), a robust bacterium that naturally secretes limestone in specific conditions [149,150]. The first prototype was an experimental material technology of self-healing concrete made by adding self-healing agents (bacterial spores) to the conventional concrete mix. Besides self-repairing, *S. pasteurii* can be used to grow building material (brick) with a biological cementation process [151,152]. In [153], researchers explored further the bacterium *S. pasteurii* using the biomineralization process of the bacteria to assemble sand particles into multi-formed cubes [154].

Similar to algae, cyanobacteria are green microorganisms (also known as blue-green algae) and are very widespread in the marine environment. The cyanobacterium *Synechococcus* is a photosynthetic organism. Instead of emitting CO_2, *Synechococcus* uses CO_2 and sunlight to grow and, in the right conditions, create a biocement, which we use to help us bind sand particles together to make a living brick. A group of researchers led by Prof. Srubar at the University of Colorado uses *Synechococcus cyanobacteria* mixed with sand particles and hydrogel to create a self-replicating brick [155]. Future research is needed to develop different growth conditions of the bacterium further, as for the moment, the favorable condition is only humidity; thus, this process does not work well in arid conditions.

Recent research shows the use of bacteria to calcify knitting into construction materials [156,157]. Architects and designers Bastian Beyer and Daniel Suarez use the bacterium *S. Pasteurii* to solidify knitted textile structures that can be used as construction material [158,159].

Bioluminescent bacteria are another group of organisms that can generate biological light. Together with the *dinoflagellates* (bioluminescent algae), they create a milky sea phenomenon on the surface of calm waters [160]. The glow emitted by the light continues for days until it fades away [161].

Researchers, designers, and architects have gradually been experimenting and studying the biological light production by bioluminescent organisms; most are microorganisms like *dinoflagellates* (bioluminescent algae) as reviewed in the previous section, and as referred to above, the two main types of bioluminescent bacteria used are *Vibrio fischeri* and *Photobacterium phosphoreum.* In some ways, the use of bioluminescent bacteria in design is still in the experimental stage and mainly for artistic and aesthetic purposes [162–164]. However, recent research and development have gradually integrated bioluminescent bacteria in their design process or production for ecological purposes, such as passive light. For example, the Ambio Light is a lighting fixture that employs the bioluminescent bacteria *Photobacterium,* isolated from the octopus, as a light source. The fixture has a glass tube containing the media with nutrients and weights on both sides for the movement. With mechanical agitation, weights create the swing movement that makes the bioluminescent bacteria glow for up to 20 min [165].

In France, *Glowee* is a Paris-based start-up drawing its inspiration from marine creatures to create bioluminescent lights powered by bacteria [166]. *Glowee* develops bioluminescent lights with environmental biotechnology and demonstrates this in a number of ephemeral installations. *La Glowzen room* innovation wellness is an interior space (a room) of relaxation with a bioluminescent ambient. The lighting solution includes genetically modified *E. coli* bacteria with bioluminescent genes inside a solution that provides nutrients for the bacteria. Encapsulated liquid provides glow under various shapes like lamps, sticks, or aquariums and offers alternatives for many uses of light. The *Château de Chapeau Cornu*, France, is the first place in the world to integrate a bioluminescent relaxation area [167]. The model of bioluminescent bacteria to light public spaces is envisaged to be installed in different locations; one has already been piloted in a waiting room at Paris-Charles de Gaulle airport.

Recent research developed the bioluminescent properties of bacteria (and other organisms) to compensate for conventional light or bioluminescent devices that can be used for public ambient urban lighting, but it is still at the laboratory scale [168]. Some conceptual urban scale projects, such as Bioluminescent devices by Eduardo Moyoral Gonzàlez [169], living lighting that employs the bioluminescence of populations of microorganisms: *Pyrocystis fusiformis* algae, *Vibrio fischeri* bacteria, mycelia, etc. The concept proposes the design and fabrication of bioluminescent glowing devices that can compensate for electricity consumption during the night. The proposal envisions several applications of bioluminescence on the streets, in public parks, on high-way posts, on signs, and in shelters.

Most recent research focuses on the use of advanced digital simulation and 3D print technology to improve the life span and light performance of bioluminescent organisms. Notably, in the '*Imprimer la lumière*' project [170], researchers focus on examining living bioluminescent bacterial substrates as architectural building materials. Two bacteria species, *V. Fischeri* and *P. Photobacterium*, are studied and developed computational models for simulating the behavior, growth rates, and life span of the living material and interface these with an architectural representation framework. Different geometrical digital prototypes are created to see how architecture can host living organisms in the most appropriate environment, at the same time, in symbiotic with building material design [171,172]. The examination is still in the preliminary stage. Further research and development of the '*Imprimer la lumière*' project will continue the new phase with the ongoing project, '*ImpressioVivo*', until 2025 [173,174].

Despite many positive potentials, there are still a number of challenges integrating living organisms as part of design productions. The limitations remain on how to keep the living organism alive in a favorable condition to suit design contexts, particularly large-scale productions in architecture.

In the next section, we present the selected case studies focusing on the use of living organisms in architectural design contexts.

3. Materials and Methods

In conducting this study, we commenced with a thorough literature review, drawing upon foundational works in architectural design that explored the historical context, theoretical foundations, and contemporary applications of living materials. Complementing this, we identified and analyzed three case studies that provided practical insights into the integration of living organisms in construction processes. To capture on-the-ground perspectives, we conducted semi-structured interviews with the relevant professionals in the field, including architects and designers, incorporating methodologies advocated in relevant qualitative research literature [175]. Synthesizing information from the literature, case studies, and interviews, we categorized recurring themes, performed a comparative analysis, and identified opportunities and limitations associated with the use of living materials in architectural design. This comprehensive approach ensured a well-rounded exploration, and throughout the study, relevant literature enriched each methodological step, contributing to a nuanced understanding of the subject. The stages of this approach are illustrated in Figure 8 below.

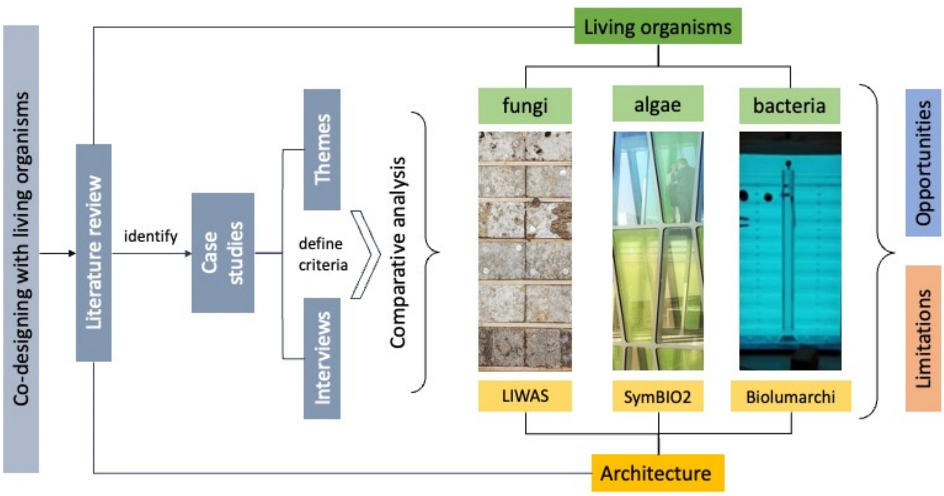


Figure 8. An illustration depicting the stages (from left to right) and aspects of the methodology. It encompasses literature review, case study identification, semi-structured interviews, defining themes, comparative analysis, and the identification of opportunities and limitations in using living materials for architectural design and construction.

Numerous architectural design experiments involving living organisms have been conducted [176–179]. For the purpose of this investigation, three specific case studies were chosen: (1) the Living Wall System (LIWAS)—featuring a myceliated façade; (2) Biofaçade SymBIO$_2$—a system fostering microalgae symbiosis within the building; and (3) Biolumarchi—exploring bioluminescence for potential applications in architectural projects. These cases were selected for specific reasons: they translate living design concepts into tangible prototypes and demonstrations tailored for architectural functions and construction contexts, and they showcase the use of distinct organisms, namely mycelium, algae, and bacteria. The subsequent sections provide detailed descriptions of each of the three selected case studies.

3.1. Myceliated Facade of the Living Wall System (LIWAS)

The Living Wall System research project was conducted in 2018 at the University of Akron during Thibaut Houette's Integrated Bioscience PhD with Integrated Bioscience PhD candidate Ariana Rupp, Tiered Mentoring student Brian Foresi, Assistant Professor of Ceramics Drew Ippoliti, Field Station Manager Lara Roketenetz, Lecturer and lab coordinator Jeff Spencer, and Associate Professor of biomimetics and director of the Biodesign lab Petra Gruber. The project was composed of two main parts: the myceliated facade and the leaf-inspired ceramics facade. The myceliated facade was built to scale up the upcycling manufacturing process outside of a laboratory and evaluate the durability of mycelium-based materials under outdoor conditions [80]. The design, research, and production were performed by Thibaut Houette, Petra Gruber, supervisor of the PhD, and Christopher Maurer—architect and founder of Redhouse Studio—growing mushroom-based materials for architecture [180], with the help of Brian Foresi. This summer project started with a literature review in May 2018, and the final facade was installed at the Bath Nature Preserve, OH, USA, in October 2018. Following the installation, a continuous assessment was performed to evaluate the outdoor durability of the various mycelium-based panels produced with different post-growth treatments.

The experimental project focuses on the potential of implementing biological organisms in facade prototypes and keeping them alive to serve in material production and building operation stages. This research project brings the integration of biological systems in architecture one step closer to changing current practices in the building industry by scaling up the manufacturing process outside of a standard laboratory setting. In an exploration to find an optimal manufacturing process, seven different batches of myceliated panels were produced in a DIY lab setting inside Redhouse Studio's warehouse, OH, USA, kept at 70 to 74°F. This type of environment limited the team's options to control temperature, humidity, lighting conditions, and the arrival of contaminants. All batches were inoculated with edible Elm oyster (*Hypsizygus ulmarius*) spawned on rye grain acquired from local mushroom farmer Valley City Fungi located in OH, USA. The seven batches were made between 6 July and 29 October 2018, to understand the effects of different manufacturing variables (i.e., substrate, sterilization/pasteurization method, and growth environment) on the mycelial growth. Five different substrates were used to produce the myceliated panels: three composed of a single ingredient (i.e., corn stover, hemp hurd, or hemp stalk), and two as a combination of multiple ingredients (hemp hurd and hemp fiber, or sawdust, soy hull, and gypsum. Three different methods were used to remove competing organisms from the substrate: exposure to ozone, submersion in a basic solution, and pasteurization. To lower the risk of contamination, the mycelium spawn was mixed with the substrates in their growth environments under a ventilation hood to lower the risk of contamination. To give a shape to the amorphous substrate and protect it from competing organisms, the inoculated materials were grown in one of the three growth environments: a bag in a frame, a frame in a box and a bag, and a tent. Panels grown from batch 2 took 3 months to fully colonize the substrate, while panels from batch 7 only took 3 weeks, showing the importance of the variables within the manufacturing process (Figure 9). After growth, four different treatments were applied: dried, baked, dried and compacted, or baked and compacted. The panels were then installed on the façade system.

Figure 9. Picture of the large myceliated panels from batch 7 measuring 130 by 53 by 8 cm grown in the tents (removed in the picture) inside the warehouse's DIY lab before being cut to 40 by 30 cm and installed façade setting. © Thibaut Houette, reproduction from Houette et al., 2020 [80].

To evaluate the outdoor durability of the façade, each panel was monitored weekly (for a year), then monthly by taking pictures of their face and side, along with measuring their thickness, texture, and the gap between the panels of each row. Out of all the post-growth treatments applied, the dried and compacted panels maintained their shape the best (Figure 10). Compacting the panels increased durability as it reduced porosity and resulted in degradation from precipitations. After the winter, fruiting bodies were observed on the unbaked panels (i.e., dried or dried and compacted), meaning that the mycelium stayed alive in this outdoor setting. As none was found on the baked panels, it can be assumed that baking successfully killed the fungus. Baking the panels led to the fastest degradations. Keeping the mycelium alive by drying it is believed to maintain its self-healing ability.

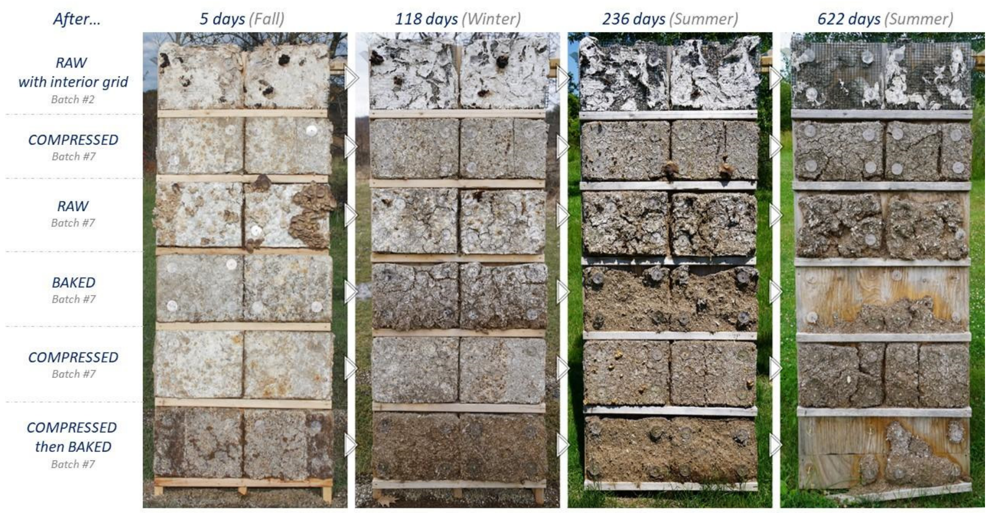


Figure 10. Evolution of the panels' durability in an outdoor setting over time. Image: Thibaut Houette.

3.2. Biofaçade SymBIO$_2$—System to Produce Microalgae in Symbiosis with the Building

The biofaçade SymBIO$_2$ project aimed to develop optimized microalgae cultivation systems (façade photobioreactors) at the front of the building by taking benefits from thermal and chemical exchanges with the host building. The inventor and coordinator of the project is the French architecture studio XTU [181], which committed several years to developing the concept of integration of algal cultures in buildings. These 'biofaçade' ideas were invented in 2008 as part of the XTU Lab_X research and innovation department (Figure 11) [182]. The biofaçade SymBIO_2 project is composed of different areas of expertise: structural engineering in complex façade, algal process engineering, thermal engineering, and glass and steel technologies, but the main partner is GEPEA laboratory (Process engineering for eco-technologies and bioresources) [183], which is part of AlgoSolis platform, an R&D innovative facility dedicated to the development of microalgae industry [184]. AlgoSolis started in 2015, and it is still active at present (Figure 11). The platform has different services and technologies working on the valorization of the microalgae with different processes that allow the exploitation of potential microalgae in all aspects, changing scales, new technology definitions, and new applications, for example, analyzing and biomass characterization, screening of strains on industrial effluents and biofaçade for microalgae culture. AlgoSolis platform, in collaboration with XTU Architects, also studied, developed, and hosted the creation of the biofaçade SymBIO_2 project with microalgae cultivation towards vertical building façade integrated photobioreactors [185,186]. There is also a doctoral thesis studying particular on the optimization of microalgae growth in façade photobioreactors for this R&D project [187].

(**a**) (**b**)

Figure 11. (**a**) Feasibility study of a biofaçade tower for ICADE by XTU Architects 2009–2011, (**b**) microalgae cultivation at AlgoSolis platform, Image credit: XTU Architects, GEPEA laboratory, Nantes University, CNRS.

The SymBIO_2 Box pilot plant was produced in 2015 (Figure 12) and was used to study and optimize the solar cultivation of microalgae on the façade of buildings, as well as the thermal symbiosis with the building. The SymBIO_2 Box has been designed to simulate different building configurations (factory, tertiary building, and block of flats).

(**a**) (**b**)

Figure 12. Biofaçade SymBIO_2 Box prototype; (**a**) Biofaçade from the exterior view, (**b**) Biofaçade inside the SymBIO_2 Box, created at AlgoSolis, GEPEA in Saint Nazaire, France, developed by XTU Architects, scientifically equipped by the GEPEA, inauguration 2015. Images: Natasha Heil.

Until present, XTU Architects continue to develop further designs and prototypes of biofaçade with microalgae, adapt and progress further from SymBIO$_2$ Box 1-1 scale prototype to suit different building typologies and needs [188]. The XTU architect team, together with GEPEA researchers, also intend to contribute to the development of 3rd generation buildings, producing biomass, environmental services, and renewable energy, as presented in project MELiSSA, an example of cultivating microalgae to create an ecosystem in the space living condition [189].

3.3. Biolumarchi—Bioluminescence Research for Potential Applications in Architectural Projects

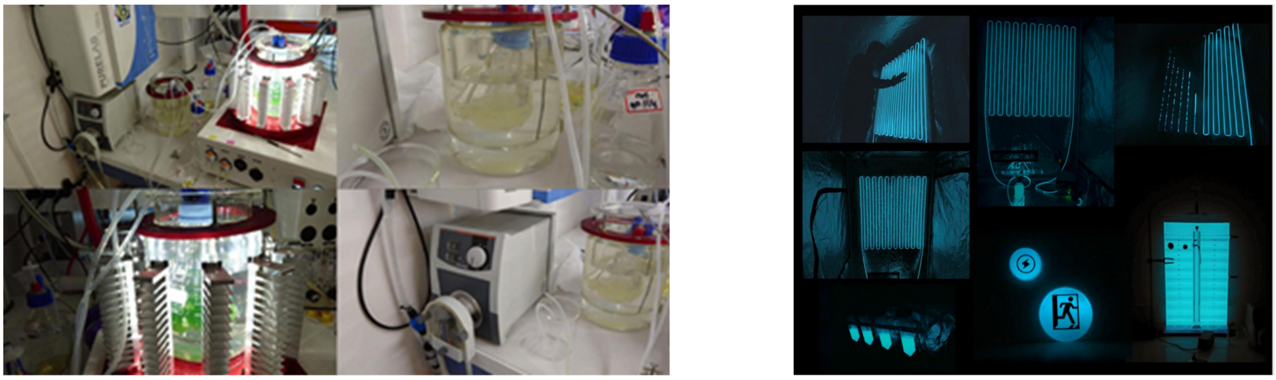
Oliver Bocquet, an architect at Rougerie-Tangram [190], has always been fascinated by bioluminescence phenomena, and he dreams of integrating this natural property to design architectural passive lighting. The first conceptual project is for the tour of Parramatta-bioluminescence applied to architecture, proposing the use of moon jellyfish with luminescent properties to apply on the glass tower façade of the Parramatta Tower in Sydney, Australia. The aim is for the town to light up itself during the night with additional bioluminescence material to glow without electricity consumption [6].

Although the project rested in the conceptual stage, because of the real-world challenges in the architecture and construction sector, O. Bocquet continued to develop the concept of how to apply bioluminescence in architecture further. The architect wanted to understand and discover the bioluminescence properties in various organisms; thus, he started to contact Christian Tamburini, a microbial oceanographer at the Marseille Mediterranean Institute of Oceanology [191]. The collaboration between Tangram Architects and the MIO has been established since 2015 at the initiative of Olivier Bocquet, an architect leading the Tangram Lab—Tangram Architects' research and innovation laboratory at that time. At MIO, bacterial bioluminescence has been studied for some fifteen years via the use and study of a bioluminescent model strain isolated in the Mediterranean Sea at a depth of over 2000 m.

With their close collaboration between O. Bocquet and C. Tamburini, together, they initiated a research and development project entitled BIOLUMARCHI: Bioluminescence research for potential applications in architectural projects [192]. Rougerie-Tangram established this R&D with MIO in the form of scientific research and engaged a doctoral candidate along with a doctoral thesis on the subject (CIFRE [193]). The work conducted during this PhD was carried out within the Environmental Microbiology and Biotechnology team (MEB) of the Marseille Mediterranean Institute of Oceanology (MIO).

The Biolumarchi project aims to understand the environmental conditions and the development parameters of bioluminescent bacteria, in particular *P. Phosphoreum* as MIO can provide the sample for developing autonomous lighting materials for architecture [194]. The thesis focuses on the development of bioluminescence stabilization and optimization processes and the exploration of urban applications [195]. A number of scientific articles have been published to discuss the Biolumarchi project, bioluminescent properties in different types of organisms, and how to develop bioluminescent bacterial culture tools and protocols for use as light sources in architecture (Figure 13) [196–198].

Several methods that we have used to collect the quantitative data and qualitative research related to each case during the period of six months are corpus (articles, books, and journals), video conferences, documents, reports, and original images provided by involved actors. Each case study involves interdisciplinary actors: architects, engineers, biomimeticians, and microbiologists. Thus, we have conducted several interviews with different actors following a semi-structured approach with a list of predetermined questions while allowing the exploration of emerging topics [199,200] (See Table 1).



(**a**) (**b**)

Figure 13. (**a**) Bioluminescent bacterial culture system, (**b**) Biolumarchi—Bioluminescence material prototype, Images credit: ROUGERIE+TANGRAM architects + M.I.O. (Mediterranean Institute of Oceanology) + CEA Cadarache (Research center of the French Atomic Energy and Alternative Energies Commission).

Table 1. Three case studies: details and methods for the semi-structured interview.

Cases	Interviewee(s)	Interviewer(s)	Medium/Date
Myceliated façade	**Thibaut Houette** (architect and biomimetician, Integrated Bioscience PhD from the University of Akron)	Natasha Heil Lidia Badarnah	Videoconference (Zoom) with recording 14 July 2023
Biofaçade SymBIO$_2$	**Jeremy Pruvost** (bioprocess engineer, algologist, director of GEPEA Laboratory and AlgoSolis R&D facility) **Alix Chiret** (biotech engineer, biologist, head of consulting and innovation at XTU Architects)	Natasha Heil Thibaut Houette	Videoconference (Zoom) with recording 26 May 2023 (Pruvost) 30 May 2023 (Chiret)
Biolumarchi	**Olivier Bocquet** (architect at Rougerie-Tangram) **Christian Tamburini** (microbial oceanographer at MIO) **Lisa Tanet** (microbiologist, PhD of Biolumarchi project)	Natasha Heil Thibaut Houette	Videoconference (Zoom) with recording 25 April 2023 (Bocquet, Tamburini) 23 March 2023 (Tanet)

After studying and analyzing the three case studies, we have discovered major common criteria and some minor differences, which are the type of living organism related to building functions and overall construction contexts, interdisciplinary framework, design and development, ethical issues, and main difficulties co-designing with living organisms. We use the set of certain values recognized through the case studies to conceptualize and design interview questions (See Appendix A). We brainstormed what we wanted to understand and achieve from the interview based on similar and different criteria extracted from the case studies.

We divided the questions into five phases: (1) Living organism(s) used, (2) Interdisciplinary collaboration, (3) Prototype, fabrication, and implementation, (4) Practicality and ethical issues, and (5) Outlook. In each phase, there were several frame questionnaires, but they were still left open for the interviewees to freely discuss their projects. The interviews were structured around the five main phases to foster the progressive deepening of the conversation. The first phase initiated with covered questions related to the selection of the living organism and its interesting properties to design functions. The second phase posed the main interdisciplinary actors involved in the projects with the following questions: what are their roles? And how is their cross-disciplinary communication? The third phase moved on to biofabrication, prototype development, technology, and readiness level [201], including future implementation of the living design as part of a building's element. The fourth discussed the ethical implications of using living organisms in design production, and the last phase described a result in relation to the design process and development: is it as expected? Or does the result change according to the living organism's conditions? And the pros/cons and further outlook of the project.

We conducted the interview via videoconferencing, and we asked each interviewee for authorization to record the video for our own use and not to diffuse it to the public. The interviews lasted approximately 50 min–1 h per participant. After the interview, we went back to study and analyze the video recordings several times, and we transcribed the interview in a text format. The raw transcriptions of the interviews were used to analyze and are presented as a result of discussion in a narrative form (coded answers from each interviewee) and in a comparative table (emergence of categories and criteria).

4. Analyses and Results

After studying the interviews and analyzing the transcriptions, we discuss each case based on our five main phases of semi-structured interview questions. We extracted coded questions and coded answers from the interview to present as the analysis result.

4.1. Living Organism(s) Used

For each project, architects selected different organisms integrated into their design according to their interests in the organism's vital properties related to design functions.

In the myceliated façade, the team composed of biomimeticians–architects grew the mycelium part of *Hypsizygus ulmarius*, also known as the elm oyster mushroom, to generate an exterior wall layer working with living material. Mycelium has the ability to turn an amorphous organic waste product into a cohesive material block with very low consumption of resources during manufacturing compared to traditional materials. The architects wanted to see what manufacturing variables could improve the growth speed and building material properties in terms of function performance and also biodegradable abilities. The use of mycelium is not only to produce building materials but also to utilize material manufacturing processes. For example, we can grow and manufacture organic materials with mycelium at room temperature. The architects only used a single fungal species as it enhances full colonization and generates more homogeneous material properties.

In the Biofaçade SymBIO$_2$ project, the architects used green microalgae for their photosynthesis capabilities to produce energy in buildings. The initial ideas of integrating microalgae in architecture derived from Anouk Legendre, associate and cofounder of XTU Architects. She participated in a scientific conference in biochemistry and discovered that microalgae are a very favorable source of renewable and sustainable energy compared to other sources, so she had the vision to integrate the role of microalgae in achieving sustainable development goals and circular economy in the building industry.

In collaboration with the partner GEPEA—AlgoSolis, they used the microalgae species *Chlorella vulgaris*, which has been cultivated at the AlgoSolis Platform in Nantes, France. The scientific partner mentioned that they used this species because it is the model they have been working with. They are precise in that there is no limit to using other photosynthetic organisms for photobioreactors, and we can cultivate all practically. For example, a blue-green microalgae or, in precise scientific terms, a 'cyanobacterium' (*Spirulina platensis*, *Arthrospira platensis*). However, green microalgae can be cultivated and reproduced quicker than blue-green ones, as mentioned by the scientists.

The architect aims to integrate microalgae in the biofaçade design to create multi-functions for building façade and systems. The microalgae façade can be beneficial for the photosynthesis process, producing energy, treating CO_2, and recovering biomass for alimentary or medical uses. Similar to fungal mycelium, they use only one species to cultivate in the biofaçade; on the theoretical principle, when we grow microalgae in photobioreactor, the problem is to accelerate 'light'—if we mix different species, the one that can grow quicker and capture more light they will develop quicker, it is like in the forest, tree that grow higher possible for the light—so that according to the strategies it is better stay in one specie.

In the project Biolumarchi, the architect has a strong interest in bioluminescence research for potential applications in architectural projects, such as passive lighting, to reduce energy consumption. The architect did not have a preference for a specific organism at the beginning; he went to discuss it with a specialist, who is a scientific partner. All the experiments conducted during this project were carried out on the laboratory's model strain, *Photobacterium phosphoreum* ANT-2200 [202]. The two main reasons they used this particular bioluminescent bacterium are as follows: One, they have several strains (a bacterial strain is defined as a subset of a bacterial species differing from other bacteria of the same species by some minor, but the identifiable difference (Moriarty et al., 2011 [203])) in the lab, which is already ongoing research at MIO. Two, *P. Phosphoreum* strain gives the most intensity of glowing light (of all bacteria bioluminescent species). They conducted different kinds of research work to comprehend the bacteria's environmental conditions before this collaboration. And they still continue to study this bioluminescent bacterial strain in symbiosis with its environments, separating from its host organism (squid or fish). Bioluminescent organisms have a very short life span, so they need to progress more on fundamental research and understand better how their life is developed before applying it in design, in particular, large-scale architectural and urban contexts.

4.2. Interdisciplinary Collaboration

In the myceliated façade project, the main actors are architects—biomimeticians (a biomimetician is an expert who works in an interdisciplinary field called 'biomimetics or biomimicry', which is the study of nature, natural phenomena, and biological principles, then transfer them into the design)—who have a good methodology in studying biological role models and transferring their principles and strategies into the design. One part of the team is composed of the PhD candidate and his supervisor, as the experiment was conducted as part of his doctoral thesis on mycelium-based composite for architecture. The other part is a practitioner architect from Redhouse Studio, who provided his knowledge on growing mycelium composite materials and his warehouse's DIY lab. He also provided the materials to grow the mycelium-based composites and helped with the manufacturing process. The actors in the myceliated façade project all took the role of biologists by gathering knowledge from all sources during the project and also from their previous experiences. All the main actors had a base understanding of cross-disciplinary biology and architectural design fields at play through previous experimentations, previous collaborations and/or literature reviews. The main actors all share a passion and interest in mycelium-based materials and their potential for architecture. They combined their knowledge during many discussions and collaborative work sessions while also learning on the fly during the experimental process. Mycologists from The University of Akron and a local mushroom farmer were also questioned along the way to better understand mycelium growth.

In the Biofaçade SymBIO$_2$, there are several partners across this R&D project, but the project is composed of two main parts: one is composed of building specialist actors (architects, structural engineer, thermal engineer, and vitro specialist), and two is composed of microalgae scientific actors (algologist, life proceeding engineer). The objective of the project was to develop a vertical photobioreactor that is able to cultivate microalgae, integrating it into the building façade. Initially, the microalgae scientists collaborated with the architects on the possibility of cultivating prototype systems, which are the complex bioengineer, life process parts, and the design that the architects needed. Once the architects understood how to maintain microalgae life within the photobioreactor, they started to propose ideas of possible photobioreactor design prototypes to best suit different building façade typologies. There are two parts: 'the function part' conducted by the scientists for the overall system of the photobioreactor, and 'the construction part' conducted by the architects for the integration of the photobioreactor into a building façade.

The microalgae scientists did not take part in the design and construction process related to the overall architectural project. The scientists worked mainly on the photobioreactor overall systems, including all related parts of utilities, to support the nutrition and control the process, temperature, and pH (potential of hydrogen). The architects collaborated with the scientists to see the possibilities of different photobioreactor systems depending on building types and climate so that the system can be adapted to optimize the development of microalgae.

Both the architects and the scientists mentioned that the cross-disciplinary collaboration was fruitful. There were some small problems in communication between the architects and the scientists because they did not know the total framework of the other field, which was normal. So, they set up some training for the cross-disciplinary team to create more links by sharing strategic points between architectural design and the microalgae façade system. Although the architects mainly put their hands on what relates to all the constraints of the buildings, they kept communicating with the scientists. All the building technical aspects also interested the scientists so that they could take into consideration overall photobioreactor optimization and development (e.g., natural light and humidity, including aesthetic design aspects).

The scientists are not involved in the integration of the biofaçade into the real building nor the commercialization part; only the architects are. But they continue to focus on searching for 'new solutions'. They are working on new technologies that can be less costly and lighter, etc., according to all the points of building requirements along with 'zero carbon' in the building. In addition, the scientists are also on the track of the valorization of microalgae in the building in terms of materials—once recovery 'biomass', they can envisage collaborating further with the architects on biobased materials for the building used.

In the Biolumarchi project, the interdisciplinary collaboration is more individual and intimate, based on one-to-one exchange. The architect had initial ideas for applying bioluminescence phenomena to passive lighting systems. Thus, the architect looked to collaborate with a specialist in the field as he was eager to learn more about bioluminescence. The architect first met the specialist (microbial oceanographer and microbiologist) and explained his passion and the conceptual idea of integrating bioluminescence into architecture. Then, they began the relationship by sharing the 'bioluminescence subject' and decided to set up an R&D project, which they thought was a constructive way to do research collaborating contract for this interdisciplinary subject.

The project is composed of three main actors: an architect who aims to apply bioluminescence as architectural passive lighting, a microbial oceanographer who works on a bacteria bioluminescent strain, a PhD supervisor, and a microbiologist who is a PhD researcher. The three actors have closely exchanged on the subject of bioluminescence throughout the project. They discussed fundamental scientific research, design ideas, and visions, whether for the development of a demonstration prototype or the project as a whole, with a shared desire to use and apply bacterial bioluminescence in a useful and reasoned way. The scientist mentioned that this R&D project gave them opportunities to work closely together, between architect and scientist. They exchanged new things both ways (biologist gives ideas on application potential, and architect on optimization). Researchers helped design projects, and the architect had an influence on the scientific research part. They mentioned that it is not normal for a microbiologist to be at the same table understanding design applications or an architect to understand profound scientific knowledge; it is a kind of new training for them.

Because they come from different backgrounds, sometimes one can raise a question about the opposite domain from a different angle. With that, they mentioned that it is very productive as it helps them to step out of their comfortable, professional field, in some way, less of a 'blinkered' view of what is possible or impossible to do than someone in the field.

4.3. Prototype, Fabrication, and Implementation

The myceliated outdoor façade panel prototype is placed at TRL 5. The team evaluated the materials produced on a temporary installation under outdoor conditions across all seasons in the Great Lakes region of the USA. They measured the prototype over multiple years to evaluate the outdoor potential of myceliated materials. The team worked on this experimental project for 6 months, from conceptualization to installation. This project served as an experimentation of the outdoor durability of mycelium material and an installation showcasing this emerging type of biomaterials to locals (i.e., installed in a nature preserve). For manufacturing optimization, there were seven batches of various combinations of substrates, sterilization/pasteurization methods, and growth environments. They went from the absence of growth to growth in 3 months and 3 weeks. The team successfully scaled up the manufacturing in a warehouse setting. For outdoor durability, it was discovered that compressing the materials without killing them led to the longest durability and that mycelium survived and was still producing mushrooms in the outdoor environment for at least a year.

The biofaçade SymBIO$_2$ box prototypes are placed at TRL 8. The team achieved the prototype at a pilot scale (pilot scale means representative engineering scale model or prototype system which is well beyond the lab scale and tested in a relevant environment. Represents a major step up in the technology's demonstrated readiness and is followed by commercialization). They installed the microalgae façade photobioreactor in an operational environment, where visitors can make a visit and walk through the SymBIO$_2$ box to feel and interact between the microalgae façade and the building's interior and exterior space. The biofaçade SymBIO$_2$ prototype has also been installed and tested for 6 months on the façade of CSTB Tower in Marne la vallée, France. The biofaçade prototype was an automated façade controlled from the platform AlgoSolis from Saint Nazaire, and it worked non-stop without any problem for 6 months. The scientists mentioned that, in general, there is no problem with cultivating the microalgae in the vertical photobioreactor; their life span could last forever (if there are no technical problems). The biofaçade is not yet in the commercialization phase, but it is very close. There are some issues to progress for a long-term real building implementation, such as the advances in technology to maintain and optimize the best life span condition of the microalgae and photobioreactor system, and at the same time, symbiosis with building façade contexts.

The researchers and scientists, on one hand, keep working on the optimization of microalgae growth in façade bioreactors. Two microalgae species (*Chlorella vulgaris* and *Haematococcus pluvialis*) were studied, as well as different photobioreactors models (laboratory and pilot scales) and culture volumes (up to 700 L). They also study the thermal behavior of the façade photobioreactor, as well as the impact of various factors on biomass productivity, namely, day/night cycles paired with temperature cycles, bubbling intensity, and scale of production [204]. On the other hand, the architect team is working on integrating and implementing the biofaçade in a real architectural project. They are working on the design and system of the prototype to suit different building needs.

For the bioluminescent architecture project, they faced several challenges related to maintaining the bioluminescent bacteria's lifespan and biolight emissions. The experimental Biolumarchi prototype is right now at TRL 3; if they pushed a bit further to do a prototype of a lamp, that would be at TRL 4, but they did not want to do it. It took them lots of time and work to create a proof of concept and a valid component in the laboratory for a bioluminescence prototype. The team mentioned that after the Biolumarchi project, they realized that it was too soon for a possible architectural application. They still need more fundamental scientific research work, perhaps combined with synthetic biology or biotechnology, to progress the life span and implementation of bioluminescent organisms. Moreover, at present, scientists do not have enough knowledge and technologies to create favorable conditions for bioluminescent organisms or to implement them in such a large-scale architectural production—there is a very high energy cost to sterilize and maintain bioluminescent organism culture.

4.4. Practicality and Ethical Issues

There are several challenges related to the use of fungal materials for architectural applications. For instance, the mycelium works as a living agent, and the set of variables that can be used to guide or control this organism's growth are not all understood. In addition, the team mentioned that they need 'a certain environment to allow it to grow'. As a result, they conducted the experiments in a warehouse's DIY lab—with relatively controlled environmental conditions. If the mycelium-based materials are grown in a space without purified air, organisms present in the environment will grow with it on the organic substrate. During the experiments, the team killed the mycelium grown on some of the panels (by baking them) and left some of them alive to observe the benefits of keeping them alive. Fabricating mycelium composite materials for large-scale applications requires a large volume of warehouse space with controlled environmental conditions. Furthermore, during the life cycle of the fungal growth, spores are released, which can be a health hazard to asthmatic people, especially at such a scale. Recent research shows a study of risk assessment of fungal materials [205].

The ethical implications of mycelium materials are relatively easy to address since the organism can be killed through heat. So, depending on the project, we can choose to keep mycelium alive and benefit from its properties or not. It depends—when we grow it, it is alive; once it is done, you bake it (heat it in the oven), and then it dies (kill it) to stop releasing spores. Mycelium can have an 'inactive or active state' to kill or to keep it alive. In most of today's packaging projects, they choose to kill total mycelium to make it safe for commercialized products. But in the myceliated façade experimentation, the team decided to leave it half dead, half alive, so that they could check the growth variables and differentiations. In addition, the great difficulties to overcome are changing 'people's mentality' about fungi (seen as a negative thing to eradicate), and it is difficult to test and compare studies from mycelium-based materials since there is no ISO standard for testing this 'non-standard building materials', so it is a big hurdle before implementation into real building contexts.

The use of microalgae in biofaçade does not pose any problem for the organism itself as microalgae are plants, not animals (if animals might be different), people prefer plants in general, and microalgae is also part of human's alimentary. The main ethical issues related to the system of biofaçade and the integration into a standard building. There are some issues to raise regarding the acceptability of highly technical systems of microalgae façade. Most people agree on the positive benefit of biofaçade, but when it comes to a real installation/commercialization, they are not sure to go for it mainly because it is not a traditional building façade. So, there are some concerns about building standards (ISO) in general, and as it is a nonstandard building façade, people are afraid of 'unknown problems'. If something goes wrong, it is difficult to solve, maintain, or find standard replacements available on the market. In addition, for example, biofaçade is excellent for treating urine and CO_2 in the building, as the topic discussed in one of the PhD theses at GEPEA [206]. To purify the urine in a station costs lots of energy and oxygen; in fact, urine is a super source for microalgae, but people are not ready to have a urine system as part of a building façade. This is still a bit of a question of social acceptance, and we also need to find better solutions and designs for the future. According to the scientist's opinion, things will change in times following the needs.

There are also challenges related to building standards. Bearing in mind that health and safety studies have been carried out for the biofaçade in implementing biofaçade into real buildings relation to buildings and habitats, but it is still not enough to fulfill all real building requirements. For example, insurance issues—all the parts of integrated photobioreactors—need to identify who insures them—architects or clients? Taking a breakthrough innovation into commercialization is still a challenge.

The bioluminescence project's main ethical issue is not concerned with the use of the bioluminescent bacteria. They used living bacteria (natural ones) and did not manipulate the genetics. They cultivated bacteria by taking one or more bacteria from seawater and using the same strain for 15 years. Keep the strain at −80 °C within their laboratory environment (MIO). The ethical issue is more about the context in which they would like to apply bioluminescence in architectural applications, which relates to ecological issues. During the Biolumarchi project, the team faced some difficulties in terms of application. Bioluminescent bacteria needed to be kept in sterilized conditions (costly in energy), and also, it needed to give enough carbons, vitamins, and all things bacteria need to grow. And if they want to have bioluminescence constantly, they need pumps and large volumes, which are very expensive in many terms and costly resources. If we want to apply bioluminescence at a large scale, it pushes us in a linear way, not a circular way. The initial intention of the architect is to compensate for electricity used with bioluminescence as passive lighting, but it is not ready yet (advances in living systems and technology). Architecture is not a good scale (yet) for bioluminescence applications.

4.5. Outlook

The outcome of myceliated façade experimentations is to investigate the outdoor durability of the myceliated façade. It was discovered that compressing the materials without killing the mycelium totally led to longer durability and that mycelium survived in the outdoor façade environment for multiple years by still producing mushrooms.

Unfortunately, the University does not have funds to continue further the prototype development, so after this project, the team also looked at other uses of fungi in human society (mycoremediation, food, and medicine production) and worked on combining them with material manufacturing. The team also continues to work on assessing the compressive and bending properties of different combinations of variables to identify their potential building applications. The outlook is to control the living organism's growth, manufacturing on a large scale and outside a laboratory workshop setting. Others are on the change of mentalities, the view we have in standard buildings, to combine functions across disciplines to understand better the use of living towards a sustainable built environment and to provide a mutual relationship between the natural environment and architecture (creating natural habitat, supporting the growth of living organisms, etc.). We need to understand what fungi can benefit in other domains that we can apply in the construction sector. Moreover, building regulations and standards should also be adopted to suit these progressing non-standard organic/living materials so that they can move a step forward to real building integration.

For the microalgae façade project, the team made a development for a 1-1 scale prototype (as seen in SymBIO$_2$)—which is an important step as the team did the validation of the system. Now, it needs to push until a commercialized project, an integration of the biofaçade in a real building and usage, in which the scientists are not involved in this final phase, only the architects. For a future outlook of the photobioreactor system, the scientists/researchers team are working on the environmental impact of 'the entire system', which includes both the 'functional part' and the 'construction part' so that they do not focus only on the photobioreactor alone but also in many other possible variables related to the building sector to integrate the microalgae façade. They need to adapt all these variables to suit the needs of microalgae. Right now, the technology is a bit generic, and they cannot achieve all at the moment. Moreover, they keep progressing on future biofaçade systems to suit different thermal and climate conditions (not the whole world climate classifications), but they try to work on the system to adapt to various conditions as much as possible, for an example, they are collaborating with The University of California, Los Angeles (UCLA) to study concept in this specific climate semi-arid like to optimize better microalgae cultivation.

The architect team is working on implementing the biofaçade into a real building. Unfortunately, the first implemented project in 2019 (a building in the 3rd district of Paris) was canceled due to the rising cost of materials (and also during the pandemic period). It was also complicated to add the biofaçade to an existing building. The main constraint relates to the building site and registration, and it is not related to the biofaçade system itself. The architects keep developing biofaçade design prototypes to best suit different building typologies. At present, they envisage integrating the biofaçade demonstrator into a façade of a single residence architectural project in Luxembourg. The architects prefer to start with a small-scale façade to test how the system works before implementing it on a bigger scale. Moreover, the selected location—Luxembourg—is very keen to innovate with environmental laws that are stricter than in France, so they are looking to push innovation in buildings even further. But beyond the small-scale façade, the architects aim to apply it to larger surfaces, which makes the biofaçade system more profitable.

The architects mentioned that the main outlook is to invest in the 'construction and commercialization' parts of the biofaçade. There are several issues that need to be considered related to a building's regulations with its inhabitants. For example, the first issue is 'security'—the level of insurance of a non-standard microalgae façade can be very complicated. Building specialists (today) do not have enough knowledge of the microalgae façade (how it works, the necessity of microalgae, how to maintain the system, etc.) to push the biofaçade in a real architectural project; they need lots of time to exchange and communicate. One of the main inconveniences is maintenance because microalgae are living things, so they can die (but the scientists have been developing a good system that can maintain microalgae pretty well), and also sometimes people are afraid of contamination or disease that might come from the microorganism, but these can be improved in the future. One other improvement to be made is to develop 'a business model' to suit a non-standard microalgae façade in architecture and building industries. We should develop a supply chain for finished products using algae. It is okay to produce the algae, but the business model depends on the recovery/sale of microalgae. If we create more seaweed products, they can be more accepted in society (less anecdotal).

The main outcome of the Biolumarchi project is a proof of concept using bioluminescence as passive architectural lighting. The team faced several constraints related to the bioluminescent organism itself as it is a 'live light', so it is still impossible to control. Bioluminescence still has a lot to explore and develop in a fundamental research phase, not yet for an application. The architect confirms that bioluminescence is a really fascinating natural phenomenon, but it is not yet applicable in real-world usage, particularly in relation to saving resources, energy, and ecological issues. Although it is not ready for today, there is good potential for progress that can be possible in the future. The future design should focus on creating 'a new system' that can reduce energy for sterilizing conditions to keep the microorganism alive (prolonging the bioluminescence phenomena). At the moment, this needs lots of energy and resources to sterilize the system, which bothers them, so they continue working more on prototypes, particularly aimed at implementation in architecture.

The architect and the scientist remain in a close relationship, and they are still collaborating on a new project on bioluminescence but not for architecture. They aim, in artistic contexts in collaboration with artists, to apply bioluminescence on a smaller scale and with less regulatory requirements (in design). They wish to demonstrate the use of bioluminescence for nocturne needs. One aspect they aim for is education, as they think it is also another way to show people how to maintain bioluminescent organisms in general before we apply it in building sectors.

As seen from the analysis and result, we demonstrate the three cases in comparison to one another in each section based on important criteria to understand the use of three different types of organisms applied in different design processes, functions, and architectural applications. We also show how scientific discipline cross-collaborates with creative design discipline to achieve the best result of co-designing with the living organism. Ethical issues are also raised, particularly in relation to overall ecological awareness. The different outcomes show different levels of prototype development depending on the characteristics and living conditions of each organism, including the way they integrate into different design functions to suit specific architectural contexts and construction requirements.

5. Discussion

The three case studies show the advantages and constraints related to the use of different living organisms in architectural design. Comparative criteria are presented in Table 2 to compare the similarities and differences according to the use and implementation of living organisms in architectural contexts.

Table 2. Comparative criteria of the three case studies: Myceliated façade (Mycelium), Biofaçade SymBIO$_2$ (Microalgae), BiolumArchi (Bioluminescent Bacteria).

Project	Myceliated Façade	Biofaçade SymBIO$_2$	BiolumArchi
Microorganism used (species)	Mycelium of elm oyster (Hypsizygus ulmarius)	Microalgae (Chlorella vulgaris)	Bioluminescent Bacteria (Photobacterium phosphoreum)
Main function (function and performance)	Exterior façade	Double skin façade	Passive lighting systems
Interdisciplinary collaboration (collaboration details, e.g., biologists)	Architects, biomimeticians	Architects, bioprocess engineers, and algologist	Architects, microbial oceanographers, microbiologists (PhD)
Project duration	6 months	5–7 years	4 years
Development stages (TRL 1–9)	TRL 5	TRL 8	TRL 3
Study type	Experimentation (showcase)	Application (demonstrator)	Experimentation (exhibition)
Motivation for using microorganisms (sustainability, performance, aesthetics, efficiency, availability, flexibility, etc.)	Sustainability (upcycling local waste to grow bio-based materials)	Sustainability (building energy consumption)	Sustainability (Passive lightings)
Application context (component, interior/exterior, insulation, pavilion, etc.)	Outdoor façade panels	Building double skin façade	Architectural passive lighting system
Ethical considerations (Yes/No)	Yes (large-scale contamination/societal acceptance/application)	Yes (societal acceptance)	Yes (application)
Raw material sources (source and availability)	Local mycelium spawn from Valley City Fungi, OH, USA, and substrates from local farmers, OH, USA	GEPEA—AlgoSolis Nantes (France)	MIO Marseilles (France) Laboratory's model strain
Challenges (contamination, unpredictable, stability, scale, environment, etc.)	Scale-up production, manufacturing location, homogeneous properties	Adaptability, maintenance, social acceptance	Life span of the organism, costly design application
Outlook (LCA, standards, installations, etc.)	Integration to building standards, large-scale health effects, material composition exploration	Photobioreactor techno progress, LCA with building for algal biomass	Research progress on bioluminescence properties

Grounding on these results, architects have similar visions of integrating 'living organisms' in their design, aiming initially at ecological awareness and sustainability, but that is not always the case; there is still a challenge to the interpretation of sustainability in using living organisms as a new ecological paradigm. The result from the interview shows several constraints in dealing with living organisms—it is still a challenge to integrate 'living' into the design process, manufacturing, and, even more, application. Moreover, the resulting designs are alive, so it is unpredictable because the process is co-performed with living organisms, and this 'new collaboration' entails a more complex relationship between vital design and the architects, who need to create a 'new mind set' between natural phenomena and manmade application. These cross-disciplinary research and development projects also bring forward the need to develop new design sensibilities to face complex interdisciplinary problems.

In architecture, scale-up design production with living organisms is the common constraint in all cases. There is still much to progress on the life span of each organism and its specific environmental condition so that it can perform its best properties. Large-scale production means multiplying the number of living organisms in design, which can be more complex than a smaller-scale production.

Comparing the three cases, the microalgae façade takes a step forward thanks to the technological advancement of photobioreactor systems that are able to provide suitable microalgae cultivation, which can help the microorganism to maintain their life better. There is some progress to further develop the microalgae façade application integrating in real buildings to suit its architectural contexts and requirements.

Fungal mycelium-based materials have already been successfully used in design products. Some of them, e.g., packaging and shoes, are already on the market as the material can be applied as biobased (dead mycelium) or living matter (alive mycelium), so the challenges depend on how the designers choose to implement mycelium-based materials in their application. There can be contamination concerns about mushrooms that release the spores when they are still alive or about the mycelium can lose some of its properties when it is dead; further studies and research need to be conducted. Moreover, the use of mycelium-based material, in combination with other organic materials, needs to progress in terms of robustness and hydrophobicity before being used in such large-scale and complex security requirements in building sectors.

The bioluminescence application is still far to reach in architectural applications as it still needs a lot more work in fundamental research to be able to keep a consistent glow and a potential of infinite lifespan, as most bioluminescent organisms emit light in a very short period (less than a second to about 10 s). It is still a big challenge to create a design prototype that can favor the bioluminescent organisms' environments and extend the life span of the organism itself. Genetic modification or advanced biotechnologies might be included in the future of bioluminescence design applications.

As shown by the three different types of living matter used: fungi, mycelium, microalgae, and bioluminescent bacteria, each organism directly affects the design process, manufacturing, and prototype/application development. Mainly because the vital properties and performances of each organism are different, they need different care to maintain life in different environmental conditions. Thus, the design and application development link closely to the vital properties of the organism—as they take part in the design process, manufacturing, and application.

There are advantages to integrating living organisms in design. Unlike traditional building design, living organisms exhibit interesting, vital properties: an ability to sense, adapt, and respond to environmental stimuli. There is a growing interest in designing with nature towards a sustainable built environment.

Several disadvantages to overcome as the use of living organisms in architecture and construction still needs further research and development to bridge the gap between laboratory research, design application, and commercial availability. This includes complex biosystems and behaviors, which are not always predictable and controllable, making them difficult to work with. One way to step further is to explore new methods and processes to co-design and co-manufacture with living organisms.

Challenges also include cost, testing, certification, and scaling up production, including consumer acceptance. The construction industry today still has a negative perception of living organisms; thinking of mold, mildew, spiders, ants, and termites, this needs a shift of perception. Researchers, scientists, or architects working on biodesign or living materials also need to address concerns about safety and biocontamination.

Designing with living organisms within the architectural realm represents a transformative shift toward a sustainable and regenerative future. To fully embrace the vision of the "new ecological paradigm", several crucial elements must be addressed. These include advanced technologies, innovative design processes, digital and biofabrication techniques, the development of biobusiness models, the establishment of building and design standards, and the shift in societal acceptance and mindset. Educating the public on the importance of co-living with other organisms, understanding their life conditions and ecosystems, and embracing the concept of buildings as vital components of the environment is pivotal.

6. Conclusions and Future Visions

This study contributes a nuanced comprehension of critical elements in the design and fabrication of prototypes that integrate living organisms in architecture. By analyzing three case studies through an in-depth literature review and interviews, the research unveils insights into the challenges and opportunities inherent in this innovative approach. The focus of the study centers on living materials such as algae, bacteria, and fungi, shedding light on their potential integration within architectural design. The findings accentuate both the limitations and advantages associated with incorporating living organisms, providing a foundation for a more holistic understanding of the implications and possibilities in this emerging field.

In looking ahead, this investigation serves as an informative groundwork for future work in the realm of co-design with living organisms. The identified limitations suggest areas for improvement and innovation, guiding subsequent research endeavors. Moving beyond the present constraints, there is an imperative need for the continuous exploration of advanced technologies, the establishment of robust bio-business models, and the refinement of design standards. As the study highlights the transformative potential of integrating living materials, the path forward involves not only addressing current challenges but also fostering an environment conducive to the dynamic evolution of architectural practices. The synthesis of knowledge gleaned from this study propels the discourse on sustainable and regenerative architectural design, laying the groundwork for future breakthroughs and advancements at the intersection between biology and architecture.

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Appendix A

Interview Questions

How long have you worked on this project? Are you still developing it?

Phase 1—Living organism(s) used

Why did you choose to work with *living organism(s) x*? Why does this particular microorganism interest you?

(Discuss the living organism, its properties, and what interests architects?)

What is the main function of integrating *living organism(s) x* in your design? What is its main performance? Does using such an organism allow you to provide multiple functions?

(Discuss how the living organism improves or changes traditional design processes, function, and performance)

Phase 2—Interdisciplinary collaboration

Do you collaborate with a (micro)biologist or other scientists?—Who are the main actors involved in this project? Who is in charge of which role for this project? How do you collaborate with cross-discipline actors?

(Discuss cross-disciplinary collaboration, how it works, and the roles of different expertise)

Interview with the (micro)biologist

Discuss with the (micro)biologist about the living organism, its properties, and if he/she takes part in the material design process and fabrication or only gives knowledge about conditions to support the living organisms—which is the case today.

And in what form does the biologist provide knowledge (send interesting articles, explain principles in presentations, discussions, fully immersed in the project development, . . .)?

Phase 3—Prototype, fabrication, and implementation

What is the development stage of your design at this point? Can you place it in TRL metric* (TRL 1–TRL 9)?

(Discuss biofabrication (design prototype with the living organism))

Is the design (or prototype) intended for implementation in building or architecture? (as a specific element?—interior/exterior façade/isolation or else?) What are the benefits of living material design compared to traditional artificial materials?

Phase 4—Practicality and ethical issues

What are your main motivations for working with living organisms as part of design?—How does it feel? What were your experiences?

Which ethical implications do you see in designing living materials? (dealing with living organisms)—especially in the architecture and construction sectors? How do you obtain raw materials—Are they difficult to obtain? Are there many sources?

(Discuss ethical issues using 'living organisms' in design, especially in construction sectors dealing with building materials standard testing and ISO building regulations for safety)

Phase 5—Outlook

Can you describe the result/outcome of your design? Is it as you expected, or does the result change according to the living organism's conditions? Pros and cons?

How do you envisage further developments and needs for the project? What could facilitate its progress? Based on your past experiences, what would you do differently?

What do you consider to be the main hurdles before the implementation of living materials (besides wood) in permanent buildings? And what about maintaining materials alive while buildings are in use?

(Discussing organism living condition needs in relation to design and implementation)

What are your personal opinions on the future of 'living materials' in the architecture and construction field?

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