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Bioreceptive interfaces for biophilic urban resilience

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Abstract

The emerging field of Biodesign sees living organisms as embedded in the design process to create bio-generated materials and artefacts. To support the growth and maintenance of these organisms, designers can adopt a Bioreceptive Design (BD) approach, recently defined as a design approach occurring every time materials or artefacts are intentionally designed to be colonized by life forms. Through this approach, the inert counterpart undergoes specific studies to reach the best bioreceptive potential for the designated life form, also considering the environment in which the artifact will be placed. In urban environments, BD examples tackle vegetation to create greener spaces and provide phytoremediation for better air quality and biodiversity in the built environment, in the wider view of nature-based solutions and climatic transitions of cities.

This study addresses the possibility of developing bioreceptive interfaces for mosses and lichens to respond to biophilic and regenerative sustainability needs in urban contexts. These organisms have contributed as pioneers, during the evolution of life on our Planet, in the formation and regulation of soil and atmosphere; moreover, they are currently used in biomonitoring actions, also contributing to the environmental awareness of the built environment. The paper proposes BD as a design approach of mutual interest, aiming at responding to the host needs and preferable environmental conditions, serving multiple species that act as co-authors of an open-ended design, increasing urban biodiversity, and providing resilient, restorative, and regenerative environments.

In particular, we present some of the results of an interdisciplinary research through design, born from the collaboration between design and biology, aiming both to bring sustainable and innovative solutions for the Biodesign and architecture sectors, but also to positively affect biological activities of biomonitoring and citizen awareness. From the design perspective, BD is applied for the selection of those material features that match the needs of the selected organism (e.g., porosity, color). Moreover, the use of Computational Design has played a crucial role in designing and prototyping bioinspired, organic shapes and textures. From a biological perspective, the research compares different methodologies for the bio-colonization of artefacts to obtain the best results for the timing and survival of the organisms. The prototypes were therefore exposed open-air with no protection or superficial treatments in a highly colonized area (from mosses and lichens), favoring the attachment of spores and propagules on the surfaces. On the other hand, some prototypes were used to test the transplant of the organisms as an alternative and faster possibility, also suitable for interior design.

This study points out how BD can be applicable when designing for the living, making clear the designer's possibilities for adopting this approach: ranging from material design to biomimicry, designing for not-only-human users, considering the host's needs and preferable growth conditions, adopting a multispecies design approach while suggesting new relationships among biotic and abiotic agents. The paper highlights how BD can provide sustainable, low-maintenance, and regenerative nature-based solutions to foster resilient urban environments.

Author keywords

Biodesign, biophilia, bioreceptive design, biomonitoring, urban resilience, green infrastructure

Introduction

The design field is increasingly aware of the limits of the current models of production and consumption, therefore looking to contribute to the transitions by proposing sustainable solutions. In particular, designers are rediscovering the material side of the projects, hybridizing their practice with materials science, chemistry, and biology, opening up a new era of interdisciplinarity driven by the research for radically sustainable materiality (Oxman, 2016). In this regard, Biodesign arises from an entanglement of design and biology as a new approach based on the involvement of living organisms in the design process (Myers, 2012). The biological origin of biodesigned materials and artefacts can lead to an organic aesthetic and a more significant presence of living organisms in the built environment. Livingness has already been recognized as a material quality in design (Elvin Karana et al., 2020). This feature leads to design systems relying on organisms' abilities to create bio-augmented products and multispecies environments. From the low to the high level of biological organization, the quality and quantity of interactions between humans and other natural agents can positively affect human wellbeing (MacKerron and Mourato, 2009). On a "microscale", recent studies recognize the importance of microbiota in the built environment for human health (Flandroy et al., 2018; Mills et al., 2019). To restore urban microbial biodiversity, Watkins and colleagues (2020) propose a framework for microbiome-inspired green infrastructures, by explicitly recognizing the microbiota's role in the functionality of an urban ecosystem (Watkins et al., 2020). Also on a "macroscale", the presence and abundance of natural/green areas is demonstrated to positively affect human health, habits, and work (Wargocki et al., 2000). Many organisms can have bioremediation effect, they can contribute in microclimate improvement, carbon storage and sequestration, noise reduction, and phytoremediation; these are just some of the benefits of plants and vegetation in urban areas (Dadea et al., 2017). Cryptogamic covers (which include cyanobacteria, algae, fungi, lichens, and bryophytes) have a significant role in the fixation of carbon dioxide and nitrogen from the atmosphere (Elbert et al., 2012), as well as reducing the runoff during the increasingly frequent phenomena of heavy rains, and providing food and shelter for other organisms, thus enhancing urban biodiversity. Many of these species, especially lichens and mosses, can also be used for environmental biomonitoring, defined as "the use of biological systems (organisms and organism communities) to monitor environmental change over space and/or time" (UNE EN 16413:2014). Lichens and mosses are currently used as bio-indicators of air quality changes in urban and non-urban environments (Contardo et al., 2020): being sensitive to air pollution, the physiological alterations occurring in polluted environments are manifested at individual and community levels. Furthermore, many species are able to bio-accumulate a large number of contaminants, providing a reliable estimate of the presence and the biological effects of those substances on the biota (Bargagli & Mikhailova, 2002). Still, natural elements also have a psychologically positive effect, addressing "biophilia", a concept introduced by the psychoanalyst Erich Fromm and, to date, highly appreciated in design and architecture (Söderlund, 2019; Soderlund & Newman, 2015). E.O. Wilson defined biophilia as "the innate tendency to focus on life and lifelike processes" (Wilson, 1984). Wilson argues that exploring life, and understanding how we are part of it, can be a profound and complex process in human mental evolution. Humans' benefits in response to a natural environment are based on our co-evolution with the natural World, and today biophilic urban design is claimed for its beneficial effects on humans' mental health and life quality (Andreucci et al., 2021). However, our current cities are far from a biophilic approach: they embed the modern aesthetic of sanitation as a value system (Pasquero & Poletto, 2020), and are planned for the confinement more than the proliferation of other species. To foster biodiversity and biophilia, urban environments should be designed to support the spontaneous growth and regeneration of living organisms, improving multispecies relationships and self-regulating and regenerative environments. Such coexistence with other organisms should be accommodated through proper design, addressing materials, surfaces, textures, spaces, and habitats. Here, the role of the inert counterpart as life-supporting material is fundamental and can be designed to better meet the organisms' requirements. In this respect, Bioreceptive Design (BD) is an approach that occurs *every time a material or artefact is intentionally designed to be colonized by one or several groups of living organisms* (Pollini & Rognoli, 2021), aimed at supporting self-regulating biotic and abiotic assemblages, designed to foster biodiversity and green spaces. This study aims to enhance the presence of lichens and mosses in urban environments through BD, by testing both material features and biological treatments suitable for an effective bio-colonization of the built environment. The selection of the organisms for this project was based on their tolerance to highly urbanized environments. The cryptogamic cover, in general, can positively affect air quality, augmenting green spaces and fastening cities' rewilding and biophilia exposure. Moreover, a significant objective of the study is the possibility of using bioreceptive materials and objects for biomonitoring activities to foster human awareness of the environmental quality of urban spaces intended as multispecies environments.

In the last years, the emphasis on improving the resilience of cities in the face of urbanization and climate change has led to the adoption of the (not still clearly defined) expression of "urban resilience" (Meerow et al., 2016). Many scholars have already related this concept to the importance of biodiversity and ecological networks (Ahern, 2013; Jansson & Polasky, 2010; Schewenius et al., 2014). Although these actions are primarily human-oriented, the dimensions of urban resilience need to tackle cities ecosystems as a whole, designing for restorative and regenerative nature-based solutions (Mang et al., 2016; Seddon et al., 2021).

Methods

This study relies on a transdisciplinary, mixed-method research approach, including design and biological methods. From a design perspective, the project relies on three main approaches: (i) Bioreceptive Design for the selection of those material features that match the organism's needs (e.g. texture, composition, porosity, color); (ii) Computational Design for the creation of special textures and shapes, followed by additive manufacturing for prototyping; (iii) Biomimicry for gathering inspiration from the natural shapes and textures increasing water absorption and spatial distribution on the surface to increase the self-regulatory ability of the system. Once the prototypes were created, the second part of the study focused on the observation of changes, by exposing the prototypes open air to evaluate the colonization status of biofilm, lichens and mosses over time.

Bioreceptive Design: bioreceptivity has been defined as "the aptitude of a material (or any other inanimate object) to be colonized by one or several groups of living organisms without necessarily undergoing any biodeterioration" (Guillitte, 1995). Pollini & Rognoli (2021) proposed to broaden the original definition, for design purposes, outlining a methodology for the design of bioreceptive materials and artefacts. This study mainly relies on this methodology, with the aim of identifying those bioreceptive material features that can facilitate the colonization by lichens and mosses. The Bioreceptive Design traditionally follows 3 steps: (i) the design of the material composition, (ii) the design of the physical characteristics of the surface, and (iii) the design of the shape of the material or artefact (Pollini&Rognoli, 2021).

Computational Design: The shift from imitation of natural forms to the imitation of the constitutive logic through which nature creates its forms appears today as one of the emerging patterns in the relationship between computational design and additive manufacturing. Layering production allows objects with material systems of extreme formal complexity. In this direction, generative design and additive manufacturing integrated with a bioinspired approach can contribute to the development of new types of products with high form, function and performance in relation to the context (Pollini et al., 2020). The computational approach plays a leading role in this context, directing the formal as well as the material conception process (Romero, 2014). Computational Design was crucial for prototyping during the 3D modelling phase, assisting the conceptual phase. Generative modelling software (Rhino and Grasshopper) was used to develop and test different textures and shapes, while additive manufacturing was employed to create the prototypes and moulds.

Biomimicry: among the biological informed disciplines, biomimicry works at the interface between physical and biological sciences (Iouguina et al., 2014). In this research, we looked for natural models for water management, from the ability of a texture to capture nocturnal humidity, to dendritic shapes to avoid excessive water stagnation. Moreover, we took inspiration from some natural patterns that distributed empty and full spaces for greater bioreceptivity.

Bio-colonization evaluation: materials' bio-colonization is a complex mechanism that occurs since the moment an object is exposed open air. The weathering, creates micro-fractures and deposit a large amount of water and nutrients other than spores and microorganisms in general on the surfaces (de los Rios et al., 2004). Biocolonization has traditionally been seen as a threaten for materials, (de la Fuente et al., 2013); however, the biofilm cover can actually play a protective role in some cases, thus the debate about the removal or not of biofilm is case-specific (Pinna, 2014). To evaluate the biocolonization stages, prototypes were exposed open air in a highly colonized location by mosses and lichens. Some tiles were previously treated by transplanting in the grooves parts or the entire body of the selected organisms, others were exposed with no treatments.

Project description

As outlined in the BD procedural thinking (Pollini & Rognoli, 2021), at first it is necessary to acknowledge the life cycle and preferred living conditions of the organisms, to create suitable bioreceptive materials and artefacts. To do so, we selected two cosmopolitan species, widespread in heavily urbanized environments: the lichen *Xanthoria parietina* and the moss *Bryum argenteum*, and we created an ID cards for both of them (Figure 1).

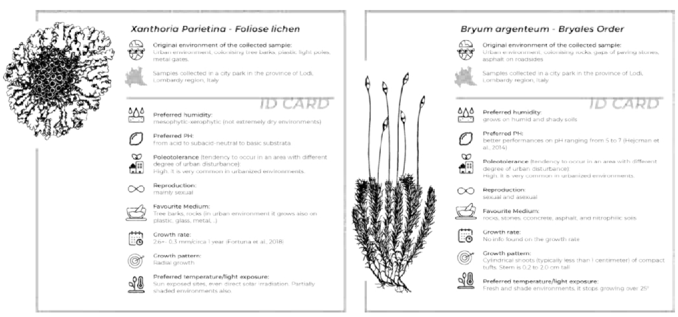

Figure 1. ID cards of the lichen Xanthoria parietina and the moss Bryum argenteum

In BD there are three levels of intervention: the material composition, the surface texture and the whole system, including the overall shape of the artifact (Pollini&Rognoli, 2021). All these variables are being tested, however the slow growth rate of the organisms is a limiting factor (Fortuna & Tretiach, 2018). Besides, we carried few other experiments as possible proof of concept for a further hypothesis of bio-colonization pattern.

To date, we have had two prototypes exposure cycles, the first since April 2022 and the second since December 2022; The project is following a reiterative investigation workflow which can therefore be subdivided in three main phases: (i) the creation of support prototypes with different bioreceptive features; (ii) the prototypes' exposure in an open environment (rooftops and similar), characterized by high lichen and mosses colonization or transplant actions (iii) the comparison between tiles with different analysis tools (e.g. microscopy) to address the degree (and success) of colonization based on the characteristics of the material and texture.

The phase of design and prototyping carried several research questions. Some emerged from the early literature in the field, which already reported about 3D printing techniques for biological colonization observing the role of microgrooves (derived by the layer-by-layer printing texture) and planned geometries (Huang et al., 2018; Mustafa et al., 2021). Other questions addressed the best integration model between biology and design, mainly focusing on creating physical samples idoneous for lichen and mosses colonization. Willing to test the bioreceptive material properties we developed different sets of tiles on which to study the bioreceptivity of the different design options by avoiding other variables; here, the tile can be considered the minimum unit of measurement to study the influence of a texture or material in terms of bioreceptivity. The design of textures was drawn through 3D modeling and parametric design (Figure 2). Parametric 3D modeling has been performed using the software Rhino and Grasshopper, particularly Grasshopper's plugin Parakeet, which provides a collection of components focusing on bioinspired and geometric algorithmic pattern generation (Parakeet, 2018).

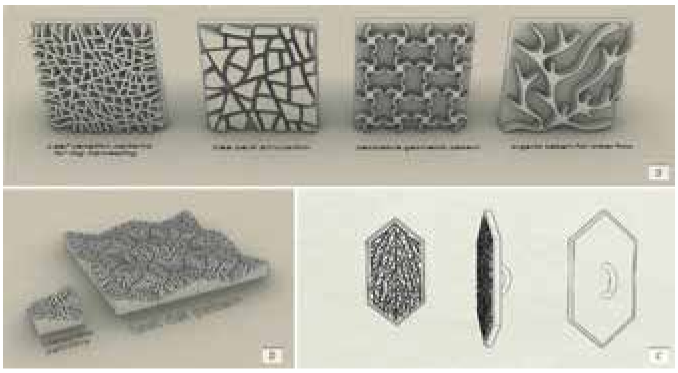

Figure 2. Computational modeling of different patterns (a. Stamps with different patterns - computational modeling; b. Tile pattern virtual testing - computational modeling; c. Stamp with pattern - computational modeling)

In the concept phase, planning the water flow has been fundamental, in fact, both lichens and mosses require high humidity but no water stagnation, meaning that the ideal substrate needs to drain water and possibly harvest air humidity without having parts of the surface where water can stagnate for a long time. Textures have been mainly bioinspired; in particular, four of them took inspiration from dendritic patterns, an archetype for growth patterns in nature (Miguel, 2014), which characterizes many natural surfaces (e.g., leaf patterns), and they can easily aid in water channeling. To better test the hypothesis that bioinspired forms could more easily be bioreceptive, two textures with purely decorative motifs have also been tested, which, however, could still channel the water without excessive stagnation. Biomimicry has been considered for the realization of textures simulating the unevenness of tree barks and leaf venation patterns, in fact, leaf venation has been tested successfully as a model for bioinspired fog harvesting (Qasemi et al., 2020), which might be ideal given the high humidity requirement that bot lichen and mosses have. Another type of tile was conceived with a dendritic pattern, but this time designed also taking into consideration a minimum hint of shape, thus approaching the third level of BD which also considers the shape. Assembling side by side several tiles, a wavy surface is obtained, with more internal movement where, in addition to the grooves that inscribe the pattern, there is a concave and convex movement of the entire surface (Figure 2 a, b, f). We choose to limit the movement of the objects in order to avoid strong differences of exposure and shading, which could influence the effectiveness of bio-colonization. The physical creation of the tiles followed using advanced machinery for 3D printing. Here, a series of prototypes in self-hardening clay, PLA, and resin were made. The PLA and resin prototypes served as models to create moulds, which were subsequently used to make clay and concrete tiles (e.g., Figure 3, c, d). Moreover, a few other samples were 3D printed in clay and suddenly fired.

Among the planned variables we had, we decided to analyze traditional building materials first, indicating further DIY-Material experimentation (Rognoli et al., 2015) for subsequent and future steps. Among the materials analyzed we have terracotta, white and red clay, mortar and concrete. Testing different materials also allows us to test the effect of different colors, material porosity and composition. Surface color is a neglected aspect in the study of cyanobacterial biofilm formation, however, color appears to influence the growth of cyanobacteria, which few study shows prefer red and white (Gambino et al., 2019; Sanmartín et al., 2020). Porosity and roughness instead are very well known and important parameters for this field of study (D'Orazio et al., 2014; Manso, 2014; Miller et al., 2012), as well as pH levels (Manso et al., 2014). The selected set of prototypes differing in colors, shape, material and superficial pattern are described in Table 1.

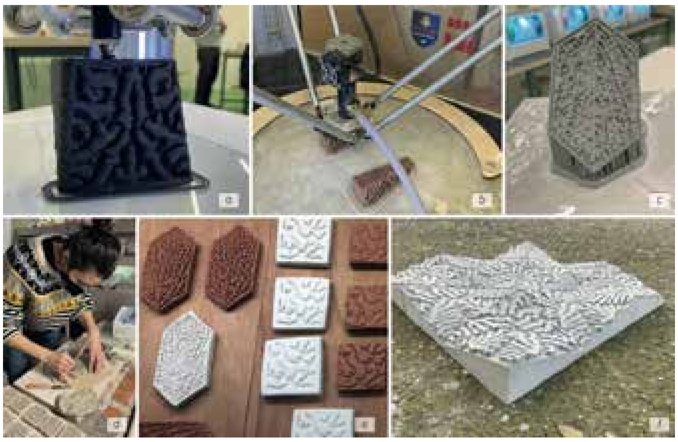

Figure 3. Prototyping process (a. 3D printed dark grey clay; b. 3D printing red clay; c. 3D printed stamp; d. Usage of 3D printed tiles as stamps; e. Clay tiles; f. Concrete tiles)

Table 1. Prototypes description

Material	Shape and size	Shape and size	Color
Hand molded clay	5x5 cm., flat	6 patterns – 6 tiles each	Red and white
3D print-ed clay	10x10cm., concave	1 pattern	Red
3D print-ed clay	10x10cm., concave	1 pattern	Dark grey
Concrete	10x10cm., concave	1 pattern	Pale grey
Mortar	10x10cm., concave	1 pattern	Light grey to white

From a biological perspective, the study compares the performance of different treatments of the materials for the bio-colonization, with the aim to obtain the best timing and treatments for our final goals. The artefacts were exposed to open air in a highly colonized environment by mosses and lichens with three different treatments. The first one is "no treatment" to see the effective bioreceptivity of the artefact per se and the textures both for lichens and mosses (and biofilm in general). The second is the "transplant" treatment, for which entire organisms (the moss Bryum argenteum and the lichen Xanthoria parietina) were transplanted on the artefacts, by exploiting their grooves to put a part of the soil and the moss, or natural glue on the prominences for the attachment of the lichen thallus. The third treatment is a different kind of transplant, since using the same technique of the method above, just the reproductive parts of the lichens and the mosses were transplanted on the artefacts. Except for the "no treatment" samples, the other two treatments were carried out separately for mosses and lichens to avoid the substratum competition between the two organisms. To test the influence of the material per se without the textures, some samples with no texture were exposed in the same environment. The different treatments aim to test the timing of bio-colonization in different "scenarios"; i.e., the absence of nutrients, the presence of adult individuals and the presence of young or potential individuals (experiments still in progress). The 5x5cm. tiles, instead, were sorted by pattern, glued to wooden supports and exposed with no treatment in natural environment (Figure 4).

First investigation from April 22: the first cycle of exposure took place a little late in the winter season due to the restrictions on access to the facilities caused by the pandemic. In any case, since April 2022, the first ceramic prototypes have been on display (and still are). Regular checks are performed to avoid excessive coverage from extraneous material (e.g., leaves) and assess the tiles' integrity. Currently, no evidence of colonization is visible to the naked eye. As time progress, we will study effective colonization and to which extent it occurs, comparing the degree of colonization between colors, patterns, materials, and shapes.

During the same period, parallel material experiments were made: (i) lichens were transplanted onto self-hardening ceramic tiles using a DIY bioplastic as glue, and (ii) silicone molds were created for making tiles testing different combinations of

Figure 4. Tile exposure (a. b. d. Siena Botanical Garden; c. e. mosses and lichen transplant; f. Tiles exposure and first colonization by green algae)

Figure 5. Analysis of green algae colonization of concrete tile (a. b. Colonized concrete tile; c. d. 40x visualization of green algae species; e. f. g. SEM observation of the green alga species "Cocconeis placentula")

cement and mortar; the latter were used for moss transplant and spontaneous colonization tests.

Second investigation from December 22: the second cycle of exposure made use of cement tiles for a more inclusive experimentation with the moss component as well. A set of 16 tiles were exposed of which 3 without treatment, 6 treated with transplants (3 for lichens and 3 for mosses), 6 with transplant of reproductive portions (as before), 1 flat tile as a control sample. Other side experiments in this second cycle were a moss colonization test by rubbing and the testing of materials with different cement and mortar gradients aimed at moss transplantation.

Early findings

Given the slow growth of these organisms, at the moment, no visible results were obtained, as expected. However, some early findings emerged from the parallel and DIY-oriented experiments: the first exposed concrete and mortar tiles in 2022 were colonized by green algae and mosses protonemata (early stages of development of mosses), considered a good sign as a pioneer species. Through SEM observation it was possible to identify the species of the green algae, that could be *Cocconeis placentula*, pioneer species of inorganic substrata (Figure 5). Such colonization corroborates the importance of the porous substrate and microgrooves pattern, typical of 3D printing, for the bio-colonization.

Moreover, the moss transplanted in January 2022 onto a cement tile is still alive, exposed outdoors. On this basis the authors decided to set up the second cycle of experiments in 2023. Also, the lichen transplant that took place in January 2022 was successful, maintaining its vitality even after a year of indoor exposure. This also paves the way for the possibility of using these bioreceptive solutions indoors, with applications for biophilic design and bioremediation (and biomonitoring) of indoor air. Our findings regarding the bio-colonization are in line with those reported by Rely et al. (2019), who tested the installation of plants on concrete mixtures for green walls, observing the persistent vitality and development of the organisms. Moreover, regarding the effectiveness of the pattern and the material's features, our findings confirm what hypothesized by Manso et al. (2014) and Mustafa et al. (2021), by working with concrete features. With this study, we aim also at highlight how BD can provide materials experiences (Karana et al., 2015), that might become significant for more-than-human users too. Living organisms cannot report considerations on the sensory, emotional, significant and performative aspects, but these levels could be evaluated based on their living response and the quality of their growth. Considering the human perspective, the material experience arises also from the relationship between the material and the organism grown on it. In this case, the significant aspect compared to traditional materials is the change over time and the perception of the living material. The proposal is to insert a transversal temporal level in the materials experience framework, which can report information on how sensoriality, emotion, performance and meaning can change over time.

Next steps – Conclusion

Thanks to this multidisciplinary collaboration, the possible outcomes of the project can be broad, contributing to biophilic urban resilience, and positively affecting design, architecture, lichenology, bryology and citizen science. The first goal of the project was the design of multiple bioreceptive surfaces to serve as support within the biomonitoring activities with lichens and mosses. The project foresees reiterative research cycles, and it is currently still in progress, oriented to understand which materials and textures are more pleasant for lichens and mosses to proliferate on. On the basis of the obtained results, we will investigate (i) a more suitable design of the tiles (ii) Different treatments before exposure, focusing on using natural medium to favor transplant (especially for lichens), (iii) material design experimentations, that can still lead to new insight, also adopting a DIY approach, offering the possibility to play with materials properties such as pH or porosity. (iv) Following the first results, new prototypes will be made for further tests, and different measurements and analyses will be possible over time concerning both lichenology, bryology, and material design (e.g., thermal insulation, oxygen production, air bioremediation, and expressive-sensorial qualities of the artefacts in terms of design opportunities).

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