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Bioreceptive Building Materials for Urban Ecology

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ABSTRACT

Bioreceptive building materials represent an emerging intersection of architecture, ecology, and materials science in which surfaces are intentionally designed to encourage colonization by microorganisms, mosses, lichens, and other organisms. Compared to traditional strategies of seeing biological growth as an act of degradation, the bioreceptive design is changing the concept of colonization to be a form of ecological provision. This review follows the intellectual lineage of bioreceptivity and how the concepts have been developed bioreceptivity is an extension of colonization receptivity, which is premised on chemical, physical and environmental factors influencing material receptivity to colonization. It takes an inventory of diverse classes of materials--literally modified concretes, ceramics, bio-based composites, and treated surfaces--with an emphasis on how each can be tuned to support biological communities. Ecological roles of such materials are as diverse as sustaining biodiversity and enhancing air quality; moderating microclimates; and carbon sequestration to augment the larger-scale green infrastructure. Concurrently, the discipline has major issues such as technical longevity, esthetics acceptability, environmental hazards and absence of standardized laboratory procedures. In prospect, the creation of multi-functional, sustainable, and digital optimized materials provides interesting lines of development. In this way, bioreceptive building materials open up a new prospect of ecologically more congruent cities where buildings are seen not as a passive framework, but as a colonizer of urban ecosystems.

Keywords: Bioreceptive Materials; Urban Ecology; Sustainable Architecture; Concrete Colonization; Biodiversity

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1. Introduction

Urban spaces are commonly depicted as an ecological wasteland these spaces are covered by impermeable surfaces, shattered habitats and lack of space to accommodate non-human species. But with urban populations ever increasing, to comprising almost three-quarters of the worldwide number by 2050, the need to reimagine cities across the ecological opportunity spectrum, as opposed to ecological absences, becomes ever stronger. Here, an area with some potential but hence far limited possibilities involves the idea of bioreceptivity, or the ability of materials to foster the growth of living things, which has been floated as a direction with promise but only in niche areas. Although some building material in traditional building science treated microbial growth on surfaces such as the growth of mosses, or other lichens as a type of degradation or fouling, newer studies are starting to consider this colonization of surfaces as a designable property and that it can play an an active and productive role in urban ecology [1,2].

The aspect of engineered or modified construction materials and the term bioreceptive building materials is created in a manner which deliberately promotes the colonization and establishment of microorganisms, flora or other biological populations. Bio-derived composites such as hempcrete or panels made of mycelium, or porous ceramics sustaining lichens, and special surface coatings that maximize water retention and nutrient availability are a few among the replaced concrete mixes that encourage moss growing, to encourage moss growth, and are examples of such longer term alternatives. In contrast to typical green infrastructure e.g., green roof, green facade, or an urban park, bioreceptive materials incorporate ecological measures already at the micro-level of material itself. By so doing, they broaden the range of strategies that may be used to develop biologically active cities [3].

These materials have great ecological prospects. Urban ecosystem services usable through colonizing organisms can be as diverse as mosses, lichens and microbes. They can control microclimates through the surface temperature moderation and moisture retention, filter air particulates, store carbon and form habitat niches used by invertebrates and other organisms. One of the potential applications of bioreceptively-designed surfaces at larger scales will be to supplement other green infrastructure by creating ecological stepping stones or micro-corridors, thus being part of the building urban biodiversity networks. The fact that ecological functions of buildings could be integrated into their very structures provides an opportunity to meet in between architectural design and relevant sustainability agendas [4,5].

Even with this promise, the study of bioreceptive materials is dispersed in between a few disciplines. Studies in materials science aim at explorations of chemical composition, porosity, and performance; in ecology, at dynamics of colonization, species interactions; in architecture, at aesthetics, saturation with form, and use of such materials to design large schemes. These views have only in the recent past started converging into a more comprehensive picture of the ways in which one can engineer built surfaces to be ecologically receptive. Further, although the scientific publication base of green roofs and green façades has been growing significantly over the last twenty years, those experiments that directly focus on bioreceptive building materials are relatively few in number, tend to be experimental in nature, and are not standardized with regard to testing methodologies [2,3,6].

The conceptualization of bioreceptivity also begs several questions of intent and ecological responsibility in design. Promoting a colonization is not merely technical question but has a component of value judgments on which species is either desirable or undesirable in a city environment. As an example, although mosses and lichens are frequently embraced because of their low-maintenance and negligible invasiveness, depending on which colonizers one is dealing with, risks may arise, including the destruction of structures and infestation by invasive species. Striking a balance between these ecological, technical and aesthetic aspects are the major challenge to the discipline [3,7,8].

In this review article, the author aims at giving an integrative review of the bioreceptive building materials in relation to urban ecology. The review is divided in six sections. The next section (Section 2) proposes the conceptual basis of bioreceptivity and the phenomena that dictate biological colonization of materials. Section 3 carries out a survey of the main categories of bioreceptive materials such as concrete, ceramics, bio-based composites, and dedicated coatings. Section 4 looks at the ecological functions and benefits of these materials, setting that material in an urban biodiversity and ecosystem services framework. The main barriers, restrictions, and research gaps have been identified in section 5 and indicate the directions of future interdisciplinary connections and innovation. At last, Section 6 provides a conclusion that dwells on the transformative power of bio-receptive substance on transforming the correlation between architecture, ecology, and materials science.By tracing the evolution of bioreceptive design from an incidental by-product of material weathering to a purposeful architectural strategy, this review positions bioreceptive materials as both a scientific and cultural frontier. Their development illustrates how the built environment can move beyond the mitigation of ecological damage toward the active fostering of ecological vitality. In doing so, bioreceptive building materials invite us to reconceptualize cities not merely as sites of human habitation but as shared ecosystems where architecture and biology co-produce new forms of urban life.

2. Concept and Principles of Bioreceptivity

The idea of bioreceptivity originated within the field of stone conservation, where scholars and practitioners were interested in explaining why some building stones supported the rapid colonization of lichens, algae, or mosses, while others resisted such processes. At that stage, the objective was largely defensive, focused on preventing biodeterioration. Over the last two decades, however, the concept has been reinterpreted more positively. Rather than resisting colonization, researchers and designers have begun to ask how colonization can be harnessed to provide ecological and aesthetic benefits. In this reframed sense, bioreceptivity refers to the intrinsic and extrinsic qualities of a material that determine its ability to support the establishment, growth, and persistence of living organisms ranging from microorganisms to vascular plants [9].

2.1. Defining Bioreceptivity

Bioreceptivity may also be thought of as the degree of ecological friendliness expressed by a material. It is not an absolute property but a property which is considered to be an epiphenomenon of the cyclical relationship between material properties, environmental conditions, and biological characteristics of colonizing organisms. Highly receptive in one environment, a material will be inert in another one. Examples of the kind of difference that may be produced are: A lump of porous cement in a wet temperate locality may soon be covered with a carpet of mosses, but in a dry, sun-exposed situation it will become sterilized in a few years. This dynamic makes clear that bioreceptivity is specifically circumstantial and demands the concomitant attention of both material science and ecology [10].

2.2. Material Properties Influencing Bioreceptivity

Achieving the extent to which a given material can accommodate biological communities is influenced by a set of both chemical and physical capabilities. The key role is played by chemical composition, and especially by pH. Very basic substrates like standard Portland cement are likely to have an negative effect on colonization, although such effects can be mitigated through additions such as pozzolanic additives or, after construction, carbonation, to provide compatibility with mosses and lichens. Porosity and surface texture are just as important physical characteristics. Coarse and porous surfaces have a higher capacity to hold water and contain microhabitat to which spores and propagules can attach whereas smooth and dense materials tend to be less accommodating. It is also of vital importance, moisture changes, as many colonizers can grow well when there is a rhythm of wetting and drying, which activates metabolic processes. Besides, the food of the material could promote or restrain biological growth. Certain substrates already contain important minerals and others need to be added or covered with a coating to supplement them. These factors do not act independently of one another but interact with microclimatic circumstances-sunlight exposure and shading, wind and the urban heat island effect- which further dictate colonization patterns [11]. The interplay of material properties and their influence on bioreceptivity is summarized in **Table 1**, demonstrating how targeted modifications can enhance ecological performance

Table 1. Key material properties affecting bioreceptivity and strategies to optimize them for biological colonization.

Property	Impact on Bioreceptivity	Modification Strategies	Example Materials
Chemical:			
pH	High alkalinity (pH > 12) inhibits colonization	Pozzolanic additives (fly ash, slag), carbonation	Portland cement, modified concrete
Nutrient content	Essential minerals support growth	Coatings with biochar/nutrient amendments	Clay bricks, ceramic tiles
Physical:			
Porosity	Higher porosity retains water and spores	Lightweight aggregates, air entrain-ment	Hempcrete, porous ceramics
Surface texture	Rough textures provide microhabitats	Sandblasting, organic burn-out tech-niques	Textured concrete, grooved bricks
Moisture dynamics	Intermittent wetting/drying stimu-lates colonization	Hydrophilic coatings, capillary struc-tures	Engineered façade panels

2.3. Ecological Hierarchies of Colonization

The colonization of building materials typically unfolds in a sequence that reflects ecological hierarchies. Microorganisms such as bacteria, cyanobacteria, and fungi are usually the earliest arrivals. These organisms alter the surface chemically and physically, often making it more suitable for subsequent colonizers [12].

The progression of bioreceptivity can be systematically categorized into distinct material stages, each influencing colonization potential (**Figure 1**). Fresh materials (e.g., unweather concrete) transition through weathering and biotic colonization, culminating in engineered states designed to host specific biological communities. These stages align with ecological succession, where early microbial colonizers modify surfaces to facilitate later establishment of mosses or lichens—a critical consideration for designing durable, ecologically active materials. Cryptogams, including lichens, algae, and mosses, commonly follow, stabilizing the surface, accumulating organic matter, and enhancing its ability to retain moisture. Over longer periods of exposure, and particularly on highly porous or weathered materials, vascular plants may take root. While these larger plants may contribute to ecological diversity and even provide microhabitats for insects, they can also raise concerns about structural damage. Recognizing this succession is crucial, since material designers often wish to favor specific colonizers—such as mosses, which provide both aesthetic appeal and ecological function—while discouraging others that might compromise durability.

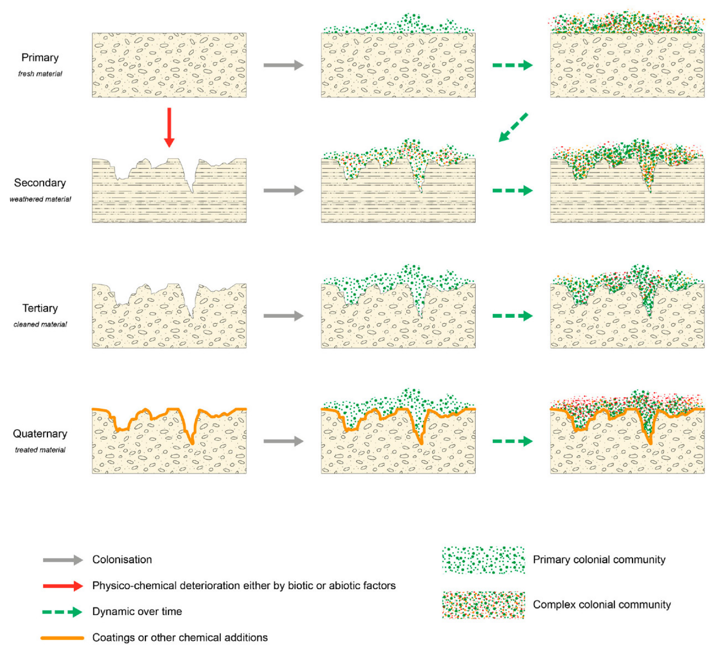

Figure 1. Visualization of the four bioreceptivity categories.

Note: The arrows indicate the changes over time.

2.4. Measuring and Assessing Bioreceptivity

Efforts to quantify bioreceptivity have employed a range of approaches, though a standardized methodology is still lacking. Laboratory experiments frequently involve the deliberate inoculation of materials with spores or propagules under controlled conditions, followed by measurements of germination rates, surface coverage, and biomass accumulation. Field trials expose candidate materials to natural weathering and colonization processes, offering insights into performance under real-world environmental conditions. Researchers have also developed indirect methods, using proxies such as water absorption capacity, surface roughness indices, or chemical analyses to infer receptivity. While each approach has advantages, the absence of consistent protocols makes comparisons across studies difficult, limiting the consolidation of knowledge in this emerging field [13].

2.5. From Biofouling to Biointegration

One of the most significant changes in the bioreceptivity discourse may be the linguistic one the switch in wording to one of biointegration instead of biofouling. Surface colonization, previously assumed only as a source of problem to structural integrity and appearance, is now being revisited as a source of design consideration. This shift parallels more general culture and ecological shifts in architecture and urban planning in which cities are now understood as an ecological as well as human system of socio-ecological systems. What comes then out of the technical expertise of bioreceptive design is therefore not only a matter of manipulating materials, but also a rethinking of the city itself as a common place. Through hosting and promoting life on the exterior of buildings scientists and architects go beyond reduction of variance on the environment and to actively promoting the ecological vitality. This educational change of view indicates a new dimension in which the liminal edges of architecture, ecology and material science are disrupted and in which the urban fabric transfers architectures themselves to become actors in the theatre of city ecology.

3. Types of Bioreceptive Materials

These trends to develop the bioreceptive building materials are based upon the idea of the emergence of various ecological opportunities of colonizing organisms that will depend upon the use of various substrates. Although all building materials are biologically colonized to some extent with time, strategic bioreceptivity design necessitates alteration or choice of material to promote desirable species and ecological processes. A variety of material classes has been explored including conventional mineral-based composites including concrete and ceramics and newer bio-based or hybrid materials. Both of them are associated with specific difficulties and opportunities on the level of their biological compatibility, durability, and use within the project toward architectural practice [1,14].

3.1. Concrete and Cementitious Composites

Concrete has been the most widely studied material in the context of bioreceptivity, owing to its ubiquity in the urban environment and its known susceptibility to natural colonization. Standard Portland cement, however, is strongly alkaline, often reaching pH values above 12, which inhibits most biological growth. Recent research has therefore focused on modifying concrete formulations to reduce alkalinity and increase porosity, thereby creating more favorable conditions for mosses, lichens, and algae. This can be achieved by incorporating supplementary cementitious materials such as fly ash, silica fume, or slag, which reduce free calcium hydroxide content and gradually lower surface pH through carbonation. Experimental methods to evaluate bioreceptive concrete often focus on water retention, a key factor for colonization [15]. **Figure 2** illustrates a standardized setup for testing moisture dynamics, featuring angled spray nozzles to simulate rainfall, textured concrete samples (e.g., waffle plates), and monitoring equipment. Such tests quantify how material modifications—such as porosity adjustments or alkaline reduction—affect the substrate's ability to sustain microbial or moss growth under controlled conditions.

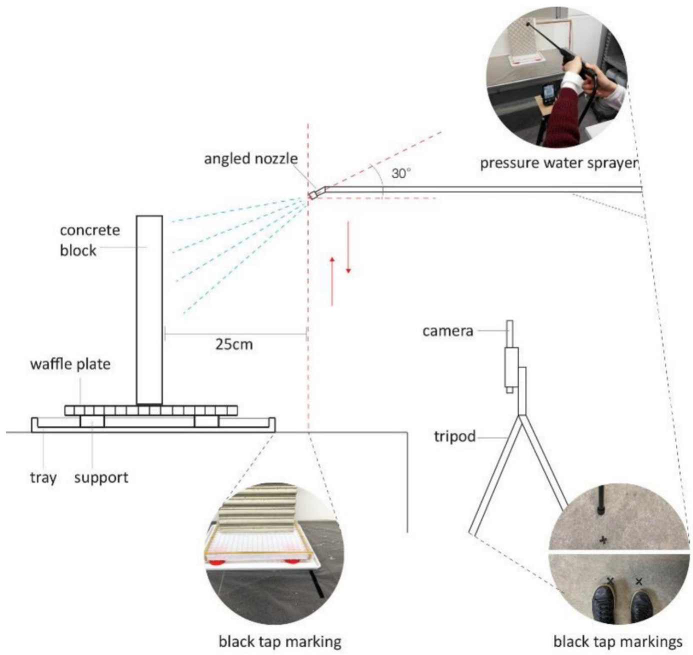

Figure 2. Setup for water retention testing on concrete panels.

Source: Robinson et al. [16].

Beyond chemical modifications, physical adjustments to the mix design—such as the inclusion of lightweight aggregates, recycled materials, or controlled air entrainment—have been used to enhance porosity and water retention. The development of "bioreceptive concrete," first demonstrated in pilot projects in Barcelona, has shown that façades and panels can be engineered specifically to encourage moss colonization, producing surfaces that not only support ecological growth but also contribute to aesthetic qualities of shading and texture. These experiments illustrate how a material once regarded as ecologically inert can be reimagined as a substrate for living systems [16].

3.2. Ceramics, Bricks, and Clay-Based Materials

Ceramics and clay-based materials, including bricks, also exhibit natural receptivity to colonization, particularly when fired at lower temperatures that preserve higher levels of porosity. The rough textures and variable mineral compositions of these materials often provide suitable niches for lichens and mosses. Traditional bricks, for instance, have long been observed to host diverse cryptogamic communities on historic structures. Unlike concrete, these materials are generally less alkaline, making them inherently more compatible with a wider range of organisms.

Modern studies have also studied ways in which ceramic tiles and cladding components can be designed to achieve a high bioreceptivity. Designers can further tune the ecological performance of a ceramic surface by manipulating the firing temperatures, inclusion of organic additions added that subsequently burn out leaving pores (ghost porosities) or selectively glazing to modify wettability. Through such patterns, the malleability of clay-based materials is emphasized, with the capability of the product to be more ecologically oriented yet at the same time durable, and aesthetically versatile [17].

3.3. Bio-Based Composites and Organic Materials

Along with mineral-based innovations, more interest has emerged in bio-based composites e.g. wood, hempcrete, and mycelium-made materials. These products are in part organic in nature and are hence naturally prone to microbial colonization. Hempcrete as a novel example, is a mixture of hemp shiv mixed into a binder of lime, which creates a light, porous material and which supports moisture regulation and can be colonized by microbial life. Mycelium composites, constructed with networks of fungal mycelium binding organic materials are a more experimental form of material which not only has the property of bio receptivity but is a form of living system in its production.

The finding of bio-based composites is that they have an ecological potential that is to bring structural performance and environmental responsiveness together. In response to this receptivity however are the trade-offs. Sometimes high bioreceptivity can be contrary to durability, because at that point colonization can speed the degradation process especially when care is not taken. What is difficult is to combine ecological value on the one hand and safety and longevity on the other, so that colonization augmented rather than impoverished the performance of architecture.

Setting up bio-based composites to be optimally bio receptive needs a balanced consideration of surface prerogative. **Figure 3** demonstrates this relationship through a classification of experimental samples (e.g., paper pulp, coffee grounds) by surface texture and meso-porosity levels. While these specific materials serve as proxies, they illustrate the fundamental principle that varying porosity and texture creates distinct microhabitats for colonization—a consideration equally relevant to scalable bioreceptive materials like hempcrete or mycelium composites.

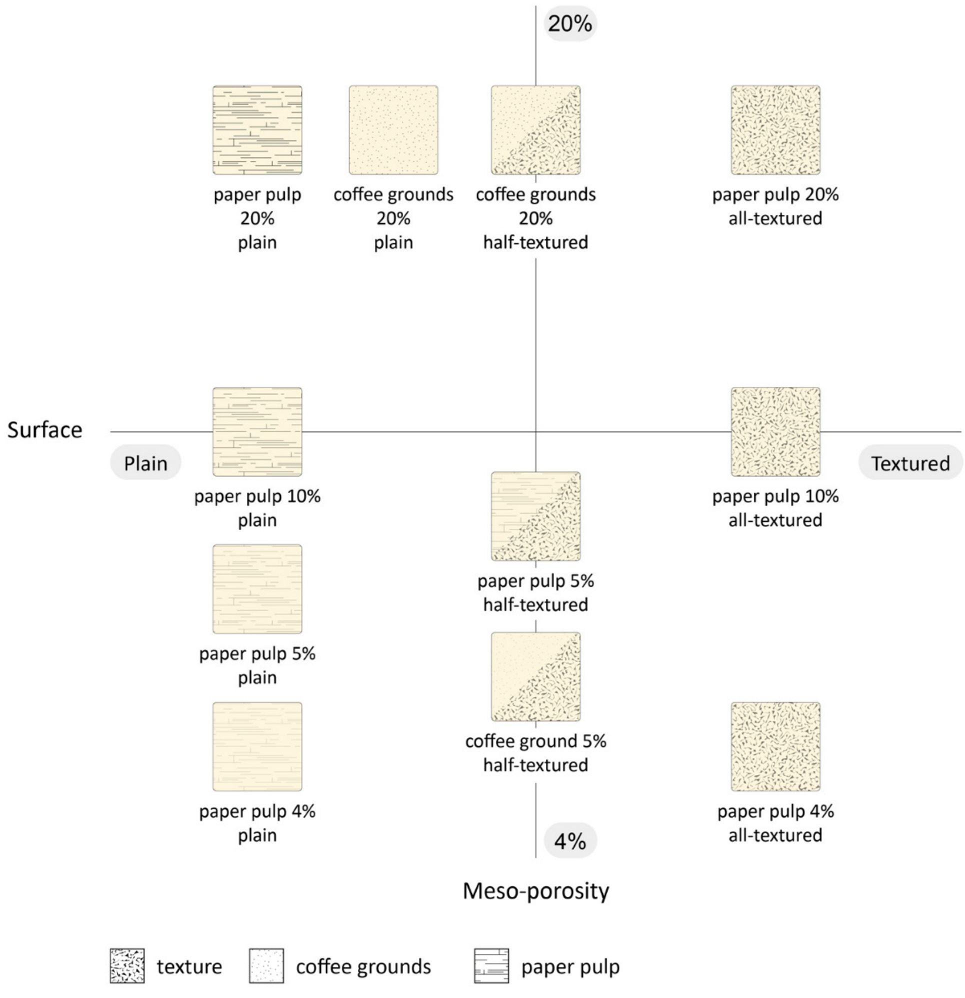

Figure 3. Relationship between surface texture and meso-porosity in experimental bio-based samples. Demonstrates how material properties create varying conditions for biological colonization.

3.4. Coatings and Surface Treatments

Another approach to bioreceptivity focuses not on altering the bulk composition of materials but on modifying their surfaces. Coatings and treatments can be applied to otherwise inert materials to render them more ecologically receptive. Mineral-based coatings that mimic natural rock surfaces, biochar-infused layers that increase porosity and nutrient retention, or textured finishes designed to hold water droplets all provide examples of this strategy. In some cases, nanostructured coatings are used to control wettability, encouraging water retention on surfaces exposed to rain or dew, thereby sustaining microbial or moss growth. The beauty of the surface treatments is that they can be flexible to use in an existing structure, providing retrofit in terms of ecological integration into a building without necessarily having to replace the material en-masse. They are also amenable to fine-tuning: certain areas of a façade may be drawn to accommodate biological communities whereas others will not be colonized, letting designers choreograph the growth pattern of living things both environmentally and aesthetically.

3.5. Hybrid and Experimental Approaches

One more group can be listed as a hybrid and experimental materials which purposely incorporate biological components in their design. Certain prototypes incorporate into prefabricated panels seeds, spores, or nutrients so that the finished material would essentially become a living facade as soon as it is installed. Some are combined with other properties, including self-cleaning photocatalysis, carbon dioxide capture or self-healing by microbial activity. Such multifunctional materials represent an emerging trend to the use of not passive, but active surfaces as a part of urban ecology and the environment.

In general, the scope of bioreceptive materials is versed to modified mineral composites, organic and hybrid systems, which contain their specific ecological and architectural aspects. Concrete and ceramics are durable and scalable, bio-based composites are more sustainable and circular, and the flexibility and multifunctionality of coating and hybrids are also in the spotlight. Combined, they comprise a heterogeneous set of tools in which the concept of bioreceptivity can be reconciled into three-dimensional practice and establish the conditions of a more enhanced interaction of ecological phenomena into the city. The diversity of bioreceptive materials and their design approaches are consolidated in **Table 2**, highlighting how material innovations balance ecological function with architectural performance [18].

Table 2. Summary of bioreceptive material classes, their design strategies, and ecological trade-offs. Each category enables distinct architectural and biological synergies.

Material Class	Key Modifications for Bioreceptivity	Target Organisms	Advantages	Challenges	Example Applications
Concrete/ Cementitious	- Reduced alkalinity (fly ash, slag) - Increased porosity (lightweight aggregates)	Mosses, lichens, algae	High durability; scalable urban use	Slow pH reduction; colonization lag time	Bioreceptive façades (e.g., Barcelona)
Ceramics/ Bricks	- Lower firing temperatures - Organic inclusions for porosity - Selective glazing	Lichens, mosses	Natural receptivity; aesthetic flexibility	Limited structural strength at high porosity	Engineered ceramic cladding
Bio-Based Composites	- Hempcrete (hemp + lime) - Mycelium-bound substrates	Microbial communities, fungi	Rapid colonization; circular material flows	Durability trade-offs; moisture sensitivity	Hempcrete walls, mycelium panels
Coatings/ Treatments	- Mineral/biochar coatings - Nanostructured wettability control - Textured finishes	Mosses, microbes	Retrofit compatibility; precise growth zoning	Long-term adhesion; maintenance requirements	Existing building façades
Hybrid/ Experimental	- Embedded spores/nutrients - Photocatalytic + bioreceptive hybrids	Custom ecosystems	Multifunctional (e.g., self-cleaning, carbon capture)	Cost; scalability constraints	Living façade prototypes

4. Ecological Functions and Benefits

Bioreceptive materials do not for this reason act as purely passive substrates into which colonization occurs, they are also important elements in urban spatial ecologies upon colonization. These materials will offer a multiplicity of ecological services which may raise biodiversity, boost environmental quality and boost urban ecosystemic resiliency by supporting communities of microbes, cryptogames and even plants in those material systems. Both these benefits are direct (e.g., servicing as habitat to organisms) and indirect (e.g., controlling microclimates and filtrating pollutants). Such an interpretation of roles is vital to understanding the worth of bioreceptive materials as ecological infrastructural components of cities [19–21].

4.1. Supporting Biodiversity

The possibility to provide habitats to a material diversity of organisms is one of the key ecological functions of bioreceptive materials. Habitat fragmentation and simplification of the ecology are common characteristics of urban environments but such phenomena can be reduced by the microhabitats offered by bioreceptive surfaces. The most common colonizers are mosses, lichens, algae as well as microorganisms and their establishment will lead to some new ecological-niches. These communities may over time harbor invertebrates (e.g. mites, springtails and small insects) that in turn serve as a substrate upon which more complex ecological interactions are built.

In that respect bioreceptive materials are miniature ecosystems built into the built environment. They do not substitute big green infrastructure like a park or wetlands, but they integrate the finer level of diversity that is otherwise lacking in highly urban environments. These materials can also act as bridge habitats that bridge discontinuous habitats, enabling diffusion of organisms through the urban grid more efficiently by providing anchor points, or stepping stones, to the adjacent environment by providing pioneer species [1,22,23].

4.2. Contribution to Air Quality and Pollution Mitigation

The colonization of organisms on bioreceptive surfaces help to clean the air in the atmosphere in a number of ways. Mosses and lichens possess the characteristics of being able to trap airborne particulates of dust and other pollutants on their surfaces thus filtering these dust and contaminants out of the atmosphere. They also take up agricultural by-products, nitrogen oxides, and sulfur, which filter down to reduce the effects of vehicular and industrial emissions as natural biofilters.

There is evidence that metabolic products of microbial communities are likely to transform or metabolize some pollutants, which is actively being studied at the moment. Although this may not be an enormous impact in small scale scenarios, thousands of square meters of bioreceptive surfaces used over a city can have a major local impact of effectively reducing the levels of air pollution in that locality given other city greening programs [24,25].

4.3. Microclimate Regulation

The increase of biological layers on the material of buildings also plays its role in regulating the microclimate on the surface and citywide. The mosses and lichens keep high levels of moisture and moderate temperature changes on the surface they inhabit. They lessen thermal stress by shading the underlying substrate, and keeping the environment at higher humidity levels to increase the life of materials.

At this building facade level, bioreceptive surfaces have the potential to passively cool through minimizing solar heating and increasing evaporative cooling. The effect is especially useful in an urban heat island environment, where there is increased proliferation of hard, heat-absorbing surfaces which exacerbate temperature extremes. Although the cooling abilities of bioreceptive materials are likely to be less significant in scale than at the level of major green roofs or vertical infrastructure, their application to expansive building surfaces may collectively help to enable urban thermal resilience [26].

4.4. Carbon Sequestration and Biogeochemical Functions

Despite their limited size, organisms that develop on bioreceptive materials are involved in global biogeochemical processes. Crops that use photosynthesis e.g., algae, lichens, mosses will store atmospheric carbon dioxide in them contributing to the local sequestration of carbon. The amounts are of course no match to forests or wetlands, and it is a dispersed and decentralized method of carbon capture, but the amounts are embedded directly into municipal infrastructure.

Also, the microbial colonizers could also accelerate nutrient circulation through nitrogen fixing, mineral solubilization or organic matter production that could add to the fertility of the substrate. These processes, when ignored too frequently, may also give dimensions on the ecology capacity of bioreceptive materials beyond the obvious vegetative cover [27].

4.5. Synergy with Urban Green Infrastructure

The bioreceptive materials can be efficiently considered as a complex of more extensive urban ecological networks. They supplement larger interventions like green roofs, living walls, street trees and urban parks by occupying the interstices which could not be efficiently covered by these systems. This synthesizing role fits the Urban Consonance framework (**Figure 4**), in which bioreceptive materials enact and embody fundamental principles such as green infrastructure hybridization and biodiversity support at the material level. Their bioturbating behavior or porous surfaces offer microhabitats which build connectivity in ecological terms throughout the built environment and their colonization processes demonstrate working socio-ecological systems at work. Bioreceptive design bioreceptive design - Bioreceptive design - Bioreceptive Buildings-183 by incorporating these functions into facades and pavements allows buildings to become full-fledged actors in urban ecological systems. As an example, green roofs will need a heavy load bearing capacity and regular irrigation and bioreceptive panels may be mounted vertically on light weight walls. Likewise, in contexts where there is less space available to plant vegetation, e.g. in the thick urbanized centres, bioreceptive materials offer prospects of exploiting biodiversity in the wall, pavement and other non utilized surfaces [1,28].

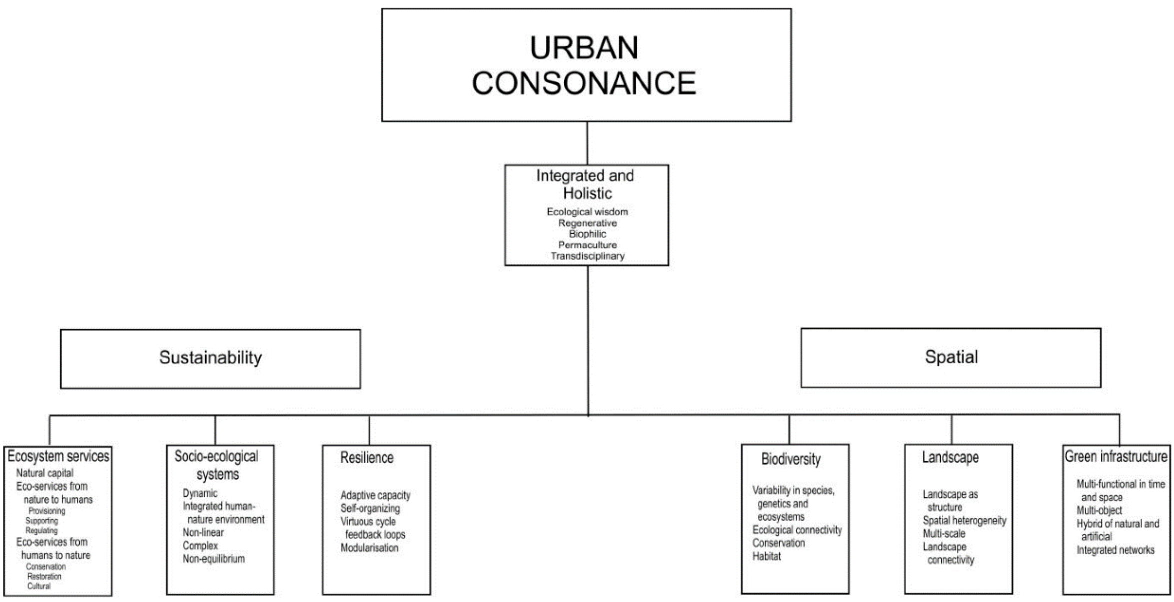

Figure 4. Urban Consonance framework, highlighting how bioreceptive materials advance biodiversity, green infrastructure, and socio-ecological resilience themes.
Source: Heymans et al. [28].

The combination of bioreceptive design with existing green infrastructure creates multi-scalar ecological networks. Microhabitats formed on building materials serve as connectors and buffers, enhancing the continuity and resilience of urban biodiversity corridors. By embedding ecological function within the very fabric of construction, cities can expand their ecological footprint without demanding additional space.

4.6. Aesthetic and Cultural Benefits

Bioreceptive materials offer aesthetic and cultural values in addition to their quantifiable ecological value. The colonizing of building surfaces by mosses, lichens, and other organisms changes the aesthetic nature both of architecture and of the building surfaces themselves by adding textures, color, and time dynamics to conventions of cleanliness and stability. These living surfaces represent the kind of organic and adaptive vision of architecture that changes with the times and is directly involved in the way it grows and changes.

This cultural aspect cannot be overlooked, because unpopularity and lack of appreciation will appear just as the social factor that will affect the use of bioreceptive surfaces significantly. Showing that colonized materials are not the kind of material that should be neglected or deteriorated, but rather they may play a great role as lively and ecologically active, bioreceptive design may effectively change the cultural perceptions of the relevance of urban biodiversity.

Ecological functions and benefits of bioreceptive materials go beyond the provision of biodiversity, air quality and enhancement, to the modulation of microclimates, carbon sequestration, and enhancement of aesthetic appreciation of built form. They work on scales both as small as interactions on the surface of materials and as large as those to ecological networks in cities. So by giving the building materials the role of providing the material skeleton of a city architecture bioreceptive design redefines the role of construction materials as a combination of not just structural and aesthetic materials but also as being a part of the ecological metabolism of a city [1,29].

5. Challenges, Limitations, and Future Directions

Although the ecological potential of bioreceptive building materials is gaining attention, their further application is considerably hindered by technical, ecological and cultural issues. The tendency to colonize setting by engineering materials poses thorny issues of durability, safety, aesthetics and unforeseen ecological change. Meanwhile, this area remains under-developed, and studies are spread over a variety of fields, and there are a limited number of testing practices available. It will be important to address these challenges in order to ensure that bioreceptive materials can enter a common usage as the part of sustainable urban architectural solutions after the experimental phase is over [29].

5.1. Technical Limitations and Durability Concerns

The difficulty likely to confront us, first of all, is that of harmonizing the biological colonizing of the materials to be used in construction with the structural and service needs of the buildings to be constructed. A large number of bioreceptive surfaces gain growth support either through elevated porosity, roughness or water retention, but the same features weaken material strength or enhance weathering. As an example, alterations that reduce the alkalinity of concrete to enable colonization by moss may similarly affect resistance to attack by chemicals. Meanwhile, freeze-thaw for cold weather could be more dangerous to highly porous ceramics. Long-term durability in a way that does not compromise ecological functioning is thus a principal technical consideration.

Maintenance is another challenge. In sharp contrast to construction materials that are intentionally designed to be mimetic to biological growth, bioreceptive-materials have management practice that requires the differentiation between desirable and undesirable colonization. Sub-dominance of vascular plants, controlling the development of weeds, guarding against invasive species, and not letting biomass get too pro-lifer [30], to trap moisture or cause mechanical damage, are all ongoing factors requiring practical implementation [31].

5.2. Design and Aesthetic Challenges

The intentional use of living things on the structures disrupts established aesthetic design in architecture, which sometimes take aesthetics of clean, smooth and unchanging surfaces as synonymous with high quality and status. Moss, lichen and other growths due to microbial patinas can be not only seen as neglect, but could be intentionally cultivated, such as by some gardens. the conflict of this issue between conventional architecture ideas of architectural cleanliness and embrace of living breathing surfaces as acceptable is a major cultural mental obstacle to adoption.

Moreover, the design practice requires a number of considerations to achieve a seemingly delicate balance between ecological mitigations and the architectural intent. The suitability of surfaces to colonization differs and choices relating to where to stimulate growth must take into factor of the load of the structure, exposure to water and aesthetic integrity. A project may seem at random or unchecked without proper planning of the colonization, which dilutes the architectural integrity of a project. Ecological vitality and aesthetic expression are key challenges that need to be developed in design strategies [32].

5.3. Ecological Risks and Unintended Consequences

Promotion of colonization also presents ecological threats that should be handled with a lot of responsibility. Mosses and lichens are usually harmless, and require little maintenance, but other colonizers can do so. Aggressive rooted vascular plants are able to enter fracture and joints damaging the structure. Accidental species that enter buildings may cause invasion to extend beyond the building surfaces, posing a threat to local biotic diversity.

It is also possible that colonization may disrupt local microbial communities and this may have unforeseen effects. As an example, the microbial growths might indicate certain release of the spores or metabolites that influence human health or the indoor air quality. Although these hazards are probably small relative to the ecological advantages, they point to the importance of a measured ecological evaluation of the use of bioreceptive materials [33].

5.4. Lack of Standardized Testing and Performance Metrics

Some significant drawbacks of existing studies are a lack of uniformity between the evaluative methods of bioreceptivity. Research is conducted under many variable and different laboratory and field procedures, such as inoculation experiments to proxy values of porosity or roughness that bar inter-comparison, or the establishment of typical performance. In the absence of standardized testing, nonscientific evaluation by architects, engineers and policymakers is difficult, in evaluating the reliability of proposed materials.

Moreover, performance has tended to be evaluated at short time scales, and there is minimal information regarding long-term colonization dynamics or ruggedness in real world environments. Identification of practical applications that follow experimental prototypes will be essential and the development of robust, repeatable and ecologically relevant methods of testing will be important [13,34].

5.5. Future Research Directions

To achieve future progress, however, bioreceptive materials could be steered in several potentially rewarding directions. Interdisciplinary research in the field of materials science, microbiology, ecology and architecture First, interdisciplinary research is required that can bridge the field of materials science, microbiology, ecology and architecture. They can be explained better by collaborative methods because of the multiplicity of interactions between substrates and organisms and urban environments.

Second, the coming materials could be multi-purposeful, as bio-receptivity with other characteristics in performance. As an example, concrete panels might be designed to actually foster colonization of moss, to sequester airborne pollutants, control the humidity levels, or to encompass auto-repair microbial activities. The ecological and functional value of the built environment would be increased by means of such multifunctional materials considerably.

Third, digital design tools and ecological modeling may be integrated so that architects can project colonization patterns and make more precise design surfaces. Computational simulations could be a solution to perfecting the surface texture, orientation, and aquatic stewardship to get preferred ecology results.

Last but not least, there is the transition in a circular economy, which unlocks new opportunities of bioreceptive design. Recycled aggregates, industrial byproducts, and low-carbon binders may also be used to create substrates that are well adapted to both sustainability and environmental receptivity. Decarbonization and resource efficiency are also linked with the concept of bioreceptive design, since the latter can support the aims of the former.

In spite of the potential of the bioreceptive building materials, technical, aesthetic, and ecological problems related to these materials, together with deficiencies in research approaches, limit their further progress. To resolve these concerns will entail creativity with material design, interdisciplinary co-laboration and cultural change in our attitude towards judging the aesthetics and efficacy of living architecture. The discipline is in its infancy, but also in an extraordinarily vibrant place where it is possible to not just advance what already exists in terms of materials, but also dream an entirely new set of kinds of ecological building systems.

6. Conclusions

The study of bioreceptive architectural construction materials is an important transformation in the relationship architecture and urban design has with ecosystem processes. Biological colonization, long considered to be a dangerous threat to durability and aesthetics is more and more reconsidered as a possibility of enhancing cities with fresh levels of biodiversity and ecological functionality. Such reframing aligns the materials beyond the role of a passive structural component, but as an active agent in the metabolism of cities.

As presented in the review, drawing on the material properties bioreceptivity is heavily informed, as shown, by both environmental factors and selecting factors, biological characteristics, and specifications (of a colonizer). Solubilization of concrete, ceramic engineering, the bio-based composites and surface treatments show that receptivity can be made deliberate, where colonization is a byproduct as opposed to a designed ecological process of integration. These materials provide nutrition to organisms, including microbes to mosses and lichen, which play many different roles in urban ecosystems, such as air quality, microclimates, carbon retention, and the development of microhabitats that stabilize urban biodiversity.

But the discipline remains young. Technical issues like adopting a balance between durability and porosity, achieving control of undesirable colonization and long-lasting performance are still unfixed. There are still aesthetic and cultural obstructions as living surfaces still problematize architectural traditions of cleanliness and durability. Although in most cases they are modest, ecological risks have to be considered to a careful extent especially with regard to invasive species and unintended microbial dynamics. Moreover, the absence of universal testing guidelines does not allow one to compare test results across time by studies, and it also impedes the process of transforming experimental prototypes into practice. Despite these limitations, the future directions for bioreceptive design are compelling. Multifunctional materials that combine bioreceptivity with pollution mitigation, self-healing, or low-carbon construction offer exciting possibilities. Integration with computational design tools could enable architects to predict and shape colonization patterns with greater precision. Circular economy principles, emphasizing recycled aggregates and industrial byproducts, could align bioreceptivity with broader sustainability goals. Most importantly, interdisciplinary collaboration between materials scientists, ecologists, and architects will be essential to realize the full potential of this emerging field.

Bioreceptive materials invite us to reconceive the city as a living, evolving system, in which architecture and ecology are not opposing forces but co-creative partners. By embedding life into the very fabric of construction, they offer a vision of urban environments that are more resilient, more biodiverse, and more attuned to natural processes. While challenges remain, the pursuit of bioreceptive design reflects a profound cultural and scientific shift: a recognition that the future of sustainable architecture may lie not in resisting nature, but in learning to build with it.

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References

[1] Cruz, M., Beckett, R., 2016. Bioreceptive Design: A Novel Approach to Biodigital Materiality. Architectural Research Quarterly. 20(1), 51–64. DOI: https://doi.org/10.1017/S1359135516000130

[2] Beyer, B., 2019. Between Duck and Tree: Metabolism-Informed Composite Tectonics [PhD thesis]. Royal College of Art: London, UK. pp. 1–317.

[3] Sanmartín, P., Miller, A.Z., Prieto, B., et al., 2021. Revisiting and Reanalysing the Concept of Bioreceptivity 25 Years On. Science of the Total Environment. 770, 145314. DOI: https://doi.org/10.1016/j.scitotenv.2021.145314

[4] Spangler, K., 2021. Bryophyte Ecosystem Services: How Bryophytes Impact Ecosystem Processes and Their Use in Urban Systems [Bachelor's thesis]. Portland State University: Portland, OR, USA. pp. 1–317.

[5] Zedda, L., Rambold, G., 2015. The Diversity of Lichenised Fungi: Ecosystem Functions and Ecosystem Services. In: Upreti, D.K., Divakar, P.K., Shukla, V., et al. (eds.). Recent Advances in Lichenology: Modern Methods and Approaches in Lichen Systematics and Culture Techniques, Volume 2. Springer: New Delhi, India. pp. 121–145.

[6] Săndulescu, R., Tertiş, M., Cristea, C., et al., 2015. New Materials for the Construction of Electrochemical Biosensors: Micro and Nanoscale Applications. Elsevier: Amsterdam, Netherlands. 1, 1–36. DOI: https://doi.org/10.5772/60510

[7] Liu, X., Qian, Y., Wu, F., et al., 2022. Biofilms on Stone Monuments: Biodeterioration or Bioprotection? Trends in Microbiology. 30(9), 816–819. DOI: https://doi.org/10.1016/j.tim.2022.05.012

[8] Bone, J.R., Stafford, R., Hall, A.E., et al., 2022. The Intrinsic Primary Bioreceptivity of Concrete in the Coastal Environment – A Review. Developments in the Built Environment. 10, 100078. DOI: https://doi.org/10.1016/j.dibe.2022.100078

[9] Jang, K.M., 2020. Moss on Rocks: Evaluating Biodeterioration and Bioprotection of Bryophytic Growth on Stone Masonry [Master's thesis]. University of Oxford: Oxford, UK. pp. 1−165.

[10] Vázquez-Nion, D., Silva, B., Prieto, B., 2018. Bioreceptivity Index for Granitic Rocks Used as Construction Material. Science of the Total Environment. 633, 112–121. DOI: https://doi.org/10.1016/j.scitotenv.2018.03.171

[11] Bissett, A., Brown, M.V., Siciliano, S.D., et al., 2013. Microbial Community Responses to Anthropogenically Induced Environmental Change: Towards a Systems Approach. Ecology Letters. 16, 128–139. DOI: https://doi.org/10.1111/ele.12109

[12] Odum, H.T., 2003. Material Circulation, Energy Hierarchy, and Building Construction. Construction Ecology. Routledge: London, UK. pp. 61–95.

[13] Guillitte, O., Dreesen, R., 1995. Laboratory Chamber Studies and Petrographical Analysis as Bioreceptivity Assessment Tools of Building Materials. Science of the Total Environment. 167(1–3), 365–374. DOI: https://doi.org/10.1016/0048-9697(95)04596-S

[14] Robinson, J.M., Watkins, H., Man, I., et al., 2021. Microbiome-Inspired Green Infrastructure: A Bioscience Roadmap for Urban Ecosystem Health. Arq: Architectural Research Quarterly. 25(4), 292–303. DOI: https://doi.org/10.1017/S1359135522000148

[15] Manso, S., Calvo-Torras, M.Á., De Belie, N., et al., 2015. Evaluation of Natural Colonisation of Cementitious Materials: Effect of Bioreceptivity and Environmental Conditions. Science of the Total Environment. 512, 444–453. DOI: https://doi.org/10.1016/j.scitotenv.2015.01.086

[16] Mustafa, K.F., Prieto, A., Ottele, M., 2021. The Role of Geometry on a Self-Sustaining Bio-Receptive Concrete Panel for Facade Application. Sustainability. 13(13), 7453. DOI: https://doi.org/10.3390/su13137453

[17] Kinuthia, J.M., 2020. Unfired Clay Materials and Construction. In: Ashour, T., Korjenic, A. (eds.). Nonconventional and Vernacular Construction Materials. Woodhead Publishing: New Delhi, India. pp. 351–373.

[18] Vaughn, S.F., Byars, J.A., Jackson, M.A., et al., 2021. Tomato Seed Germination and Transplant Growth in a Commercial Potting Substrate Amended with Nutrient-Preconditioned Eastern Red Cedar (Juniperus virginiana L.) wood Biochar. Scientia Horticulturae. 280, 109947. DOI: https://doi.org/10.1016/j.scienta.2021.109947

[19] Girardello, M., Santangeli, A., Mori, E., et al., 2019. Global Synergies and Trade-Offs Between Multiple Dimensions of Biodiversity and Ecosystem Services. Scientific Reports. 9(1), 5636. DOI: https://doi.org/10.1038/s41598-019-41342-7

[20] Pedersen Zari, M., 2020. Biomimetic Urban and Architectural Design: Illustrating and Leveraging

Relationships Between Ecosystem Services. Biomimetics. 6(1), 2. DOI: https://doi.org/10.3390/biomimetics6010002

[21] Schwarz, N., Hoffmann, F., Knapp, S., et al., 2020. Synergies or Trade-Offs? Optimizing a Virtual Urban Region to Foster Plant Species Richness, Climate Regulation, and Compactness Under Varying Landscape Composition. Frontiers in Environmental Science. 8, 16. DOI: https://doi.org/10.3389/fenvs.2020.00016

[22] Jim, C.Y., Chen, W.Y., 2011. Bioreceptivity of Buildings for Spontaneous Arboreal Flora in Compact City Environment. Urban Forestry & Urban Greening. 10(1), 19–28. DOI: https://doi.org/10.1016/j.ufug.2010.11.001

[23] Hayek, M., Salgues, M., Souche, J.C., et al., 2022. From Concretes to Bioreceptive Concretes: Influence of Concrete Properties on the Biological Colonization of Marine Artificial Structures. In Proceedings of the MARINEFF International Conference: From Materials and Infrastructures to Marine Ecosystem - Interactions and New Approaches, France, Paris, 3−5 May 2022; pp. 1−10.

[24] Singleton, I., 1994. Microbial Metabolism of Xenobiotics: Fundamental and Applied Research. Journal of Chemical Technology & Biotechnology: International Research in Process, Environmental and Clean Technology. 59(1), 9–23. DOI: https://doi.org/10.1002/jctb.280590104

[25] Díaz, E., 2004. Bacterial Degradation of Aromatic Pollutants: A Paradigm of Metabolic Versatility. 7(3), 173–180.

[26] Yang, F., Chen, L., 2020. High-Rise Urban Form and Microclimate. Springer: Singapore. pp. 1–211.

[27] Manso, S., De Muynck, W., Segura, I., et al., 2014. Bioreceptivity Evaluation of Cementitious Materials Designed to Stimulate Biological Growth. Science of the Total Environment. 481, 232–241. DOI: https://doi.org/10.1016/j.scitotenv.2014.02.059

[28] Heymans, A., Breadsell, J., Morrison, G.M., et al., 2019. Ecological Urban Planning and Design: A Systematic Literature Review. Sustainability. 11(13), 3723. DOI: https://doi.org/10.3390/su11133723

[29] Mahrous, R., Giancola, E., Osman, A., et al., 2022. Review of Key Factors That Affect the Implementation of Bio-Receptive Façades in a Hot Arid Climate: Case Study North Egypt. Building and Environment. 214, 108920. DOI: https://doi.org/10.1016/j.buildenv.2022.108920

[30] Hebel, D.E., Heisel, F., 2017. Cultivated Building Materials: Industrialized Natural Resources for Architecture and Construction. Birkhäuser: Basel, Switzerland. pp. 1–184.

[31] Graham, P., 2009. Building Ecology: First Principles for a Sustainable Built Environment. John Wiley & Sons: Hoboken, NJ, USA. pp. 1–320.

[32] Scruton, R., 2021. The Aesthetics of Architecture. Princeton University Press: Princeton, NJ, USA. pp. 1–320.

[33] Adams, W.B., Mulligan, M., 2012. Decolonizing Nature: Strategies for Conservation in a Post-Colonial Era. Routledge: London, UK. pp. 1–308.

[34] Miller, A., Dionísio, A., Macedo, M.F., 2006. Primary Bioreceptivity: A Comparative Study of Different Portuguese Lithotypes. International Biodeterioration & Biodegradation. 57(2), 136–142. DOI: https://doi.org/10.1016/j.ibiod.2006.01.003