Holobiontic architecture: from monologue to multispecies dialogue

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Abstract: Holobiontic architecture reimagines buildings as dynamic, multispecies ecosystems—spaces where humans, microbes, and environmental forces interact in continuous exchange. Within this framework, buildings are understood as *meta-holobionts*: nested assemblages of holobionts that include human occupants, microbial consortia, and environmental agents. This vision centres on the concept of the *building-as-reef*—an architectural typology that promotes biodiversity, supports regenerative processes, and secures ecological relationships. Like coral reefs, these buildings provide habitat, structure, and metabolic function, transforming the built environment into a scaffold for life.

The design strategy that shapes microbial colonization on building surfaces is *eco-ornamentation*: the intentional crafting of textured, patterned surfaces to support microbial life. These surfaces are not merely decorative; they are biocatalytic, hosting metabolically active organisms that contribute to carbon fixation, pollutant degradation, and redox cycling. In anaerobic zones, advanced bioelectrochemical systems embedded within wastewater infrastructure act as biosensors and metabolic processors, enabling buildings to sense, adapt, and participate in biogeochemical cycles.

In contrast to modernist ideals of sterility and minimalism, holobiontic design embraces *managed mutualism*, where hygiene is reconceived as the cultivation of beneficial microbial communities. Ornamentation becomes a site of ecological function, merging aesthetic expression with biological performance.

At the urban scale, individual structures operate as nodes in distributed microbial infrastructures—forming city-scale immune systems capable of responding to environmental stressors in real time. This expanded view positions architecture within a broader ecological continuum, where built forms participate in multispecies networks that span scales and domains.

Holobiontic architecture thus offers a new protocol for cohabitation: a spatial and biological contract grounded in reciprocity, ecological intelligence, and multispecies collaboration. It provides practical tools for regeneration and a transformative design ethic—one that aligns human habitation with the microbial systems that sustain planetary life.

Keywords: holobiont, eco-ornamentation, microbiome, bioelectrochemical systems, building-as-reef

1. Architecture in the age of microbial entanglement

Architecture today faces a crisis of relevance as its dominant paradigms prove inadequate to address ecological collapse. While the discipline has begun to acknowledge environmental concerns, its responses remain constrained by superficial adaptations—green façades that mask extractive foundations, net-zero narratives that obscure systemic harm, and technological fixes that overlook ecological complexity (Armstrong, 2022). These approaches perpetuate the illusion of progress while leaving modernity's exploitative logics intact. A fundamental reorientation of architectural thought is needed, one that begins with the smallest agents of planetary life.

This paper imagines architecture via a bottom-up architectural metaphysics, proposing that ecological design begins with the 'weakest' elements of life that have long been exploited—the microbes (Haque, 2019). Modern architecture conventionally regards microbial colonisation as a form of biodeterioration, something to be eradicated through biocidal materials and sterilizing regimes under the *Reign of Hygiene* (Lahiji and Friedman, 1997). Yet microbes were the original architects of the biosphere, shaping Earth's atmosphere and mineral cycles billions of years before human existence (Margulis, 1991; Rohwer et al., 2002). Their metabolic intelligence—evidenced in resilience, cooperation, and deep ecological entanglement—offers a bottom-up-first model for rethinking buildings as dynamic interfaces between human and nonhuman worlds.

At the heart of this reimagining lies the concept of *holobiontic architecture*—a framework that considers buildings as host organisms actively supporting interdependent life. Derived from biology, the concept of holobiont refers to a host and organism and its symbiotic community (Margulis, 1991; Rohwer et al., 2002). This framework operates at nested scales, from individual organisms to complex systems. Humans, for example, are holobionts, composed of host cells and microbial symbionts that influence physiological functions, immune responses and cognition (Ursell et al., 2012; Gilbert et al., 2024). However, humans also inhabit and contribute to larger holobiontic systems—such as buildings—which can be understood as *meta-holobionts*. In this extended framework, buildings function analogously to coral reefs. Just as the mineral skeleton of a reef provides structural support and habitat for symbiotic polyps, algae, and microbes (Rohwer et al., 2002), architectural structures offer affordances for both microbial and human communities. The concept of the *building-as-reef* highlights how built environments can support multi-species cohabitation, transforming static infrastructures into ecologically active systems.

The materiality of building surfaces—porosity, texture, chemical composition—selects for specific ecological relationships: concrete surfaces support the growth of lichen colonies that sequester carbon (Elbert et al., 2012), while interior materials harbour human-aligned microbiomes (Kembel et al., 2012). Architecture thus becomes a living interface, metabolising, adapting, and co-evolving with its inhabitants—far removed from modernity's sterile metaphor of buildings as "... a machine for living" (Le Corbusier, 1986, p151;Loos, 1998). The implications extend beyond technical design. By centring microbial agency as the primary design principle, holobiontic architecture challenges the necropolitical underpinnings of modernist hygiene, which seeks to maintain buildings in a state of pristine, human-exclusive stasis. Consequently, an ethic of cohabitation emerges from the very acts of design, where buildings become mediators in multispecies dialogues. This is not metaphor but material practice—from the probiotic microbiome of interior surfaces that shape human health (Ursell et al., 2012; Fu et al., 2021), to environmentally compatible bioreceptive façades that participate in urban carbon cycles (Elbert et al., 2012), and bioanodes in wastewater systems that enable resource circularity in building systems—architecture becomes a living participant in planetary metabolism (Table 1).

Building-as reef surface type	**Probiotic**	**Bioreceptive**	**Bioanode**
Primary Function	Gardening indoor microbiomes	Environmental colonisation	Bioelectrochemical conversion
Location	Interior walls, handles, furniture	Exterior façades, roofs	Wastewater systems, hidden anaerobic infrastructure
Key Microbes	*Bacillus subtilis*, *Lactobacillus*	Lichens, mosses, algae	*Geobacter*, *Shewanella*
Material Design	Textured ceramics, porous polymers, fabrics	Rough concrete, mineral coatings	Carbon felt, conductive graphene
Maintenance	Probiotic sprays, pH monitoring	Seasonal rewilding cycles	Voltage optimization, flow regulation
Performance Metrics	Pathogen suppression rates	CO_2 sequestration, biodiversity	Current density (A/m^2), maximum current generation, charge transfer

Table 1. Comparative table: surface typologies in holobiontic architecture

This transformative vision is realized through three interconnected approaches (Table 2). Firstly, eco-ornamentation reconsiders surface design, patterning materials to selectively support microbial life. Where modernist aesthetics prized sterile smoothness, eco-ornamentation embraces textures that invite colonization, turning buildings into collaborative landscapes. Secondly, Bio-Baroque aesthetics extend this logic, redefining ornament as an optimised site for supporting life—where intricate material complexity enabled by rapid prototyping systems, supports ecological performance through microbial habitats that purify air, regulate humidity, and participate in nutrient cycles. Finally, immunity-as-peacemaking completes this triad, replacing eradication with negotiation (Palazón et al., 2008) and cultivating resilience rather than enforcing sterility. Together, these principles position architecture as a site of convergence where scientific insight, cultural theory, and ecological imagination collaborate to build not just for life, but with it.

Principles of holobiontic architecture	**Concept**	**Characteristics**
1. Eco-Ornamentation	Reimagines architectural surfaces as bioreceptive environments that support microbial life. Challenges modernist ideals of sterility by inviting colonisation through material texture and biological integration.	- Bioreceptive exteriors - Probiotic interiors - Bioanodes in wastewater systems - Texture as microbial habitat

2. Bio-Baroque Aesthetics	Merges ornament and function using advanced fabrication. Microbial ornamentation becomes ecologically performative—purifying air, regulating humidity, participating in nutrient cycles.	- Rapid prototyping techniques - Intricate material complexity - Embedded microbial functions - Performance-driven ornament
3. Immunity-as-Peacemaking	Transitions from microbial eradication to negotiation, inspired by Matzinger's Danger Theory. Introduces hygiene protocols that differentiate beneficial from harmful microbes, fostering ecological and immunological resilience.	- Danger Theory framework - Selective hygiene strategies - Emphasis on microbial relationships - Resilience over sterility

Table 2. Three principles of holobiontic architectural design.

2. The building as meta-holobiont: from coral reefs to constructed ecosystems

> *"Your house is your larger body.*
> *It grows in the sun and sleeps in the stillness of the night; and it is not dreamless.*
> *Does not your house dream? And dreaming, leave the city for a grove or hill-top?"*
> — Kahlil Gibran, *The Prophet* (1923)

Gibran's metaphor of the house as a living body finds renewed relevance in contemporary biology and architectural theory. Buildings are not inert enclosures; they host complex microbial ecosystems, exchange matter and energy with their surroundings, and participate in broader ecological networks. The *building-as-reef* analogy makes this tangible: just as coral structures support diverse symbiotic life, architectural materials can be designed to promote multispecies interactions and environmental responsiveness. Holobiontic design translates this vision into material practice (Figure 1).

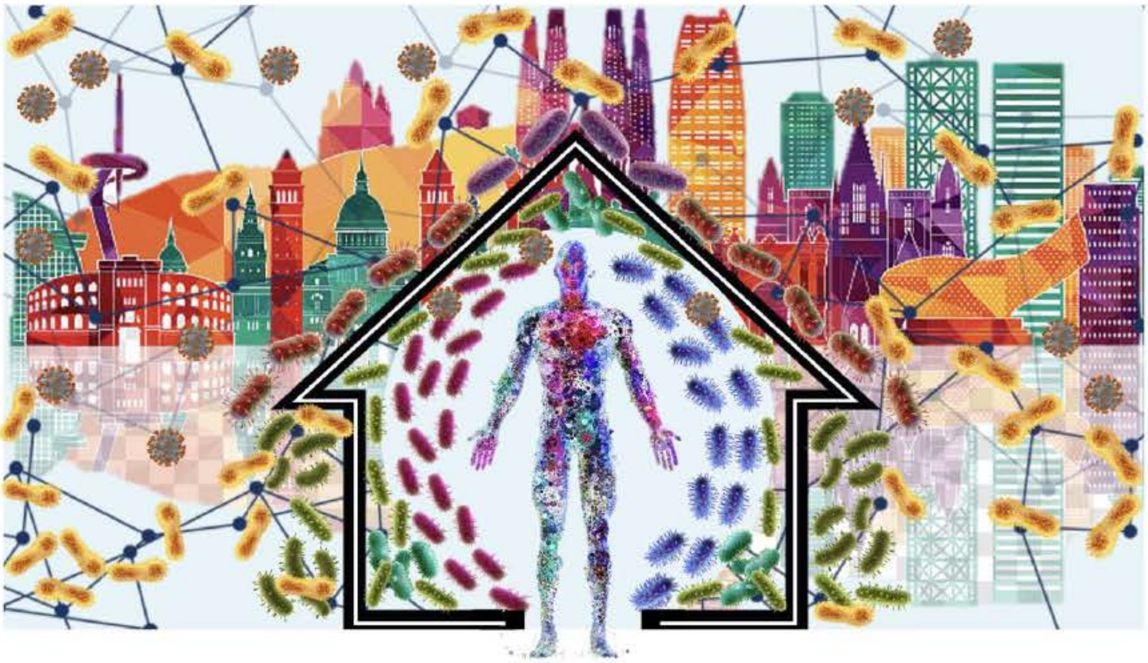

Figure 1. Architecture as Meta-Holobiont: From Human Microbiome to Urban Ecosystem. The *building-as-reef* operates as a meta-holobiont—a composite ecological system that houses and interacts with multiple layers of biological life. At its core, it shelters the *human holobiont*, which includes the human body and its associated microbiome. Surrounding this, is the *microbiome of the built environment* (MBE) comprising microbial communities that inhabit architectural surfaces (indoors, outdoors), air systems, wastewater, and materials forming an expansive network of microbial interactions. Beyond the building is the urban microbiome, another meta-holobiontic system comprised of many other buildings and their interstitial spaces and microbial theatres of activity (Whipps et al., 1988).

Rather than shielding buildings from environmental exposure, surfaces can be designed to work with local natural systems. *Bioreceptive materials*—like concrete façades that support lichen growth (Elbert et al., 2012) or brickwork textured to encourage moss colonization—act as active interfaces with the surroundings. These surfaces contribute to air purification, regulate temperature, and filter water, operating concurrently as architectural elements and as extensions of the biosphere's metabolic systems.

Inside buildings, a different kind of metabolic exchange takes place. Natural materials such as untreated timber or clay, when inoculated with beneficial microbes like *Bacillus subtilis* (Hu et al., 2022), can help cultivate healthy indoor microbiomes. These microbial communities have been shown to influence human health (Roslund et al., 2020; Gilbert et al., 2024). In this way, architecture becomes a medium of subtle biological communication—its surfaces hosting microbial processes that work in parallel with human physiology, helping to maintain the health of the *human microbiome* (Lederberg and McCray, 2001).

Within this framework, material specificity is crucial: microbial colonisation is not random but shaped by the porosity, pH, and chemical composition of architectural substrates. These properties act as selective filters, directing microbial succession in response to environmental conditions and temporal changes.

2.1 Thresholds as Ecotones

Transitional spaces—such as thresholds, vents, and drainage systems—act as ecological interfaces. These zones mediate between interior and exterior conditions, facilitating the movement of air, moisture, and microbial spores. Like ecotones in natural systems--regions of transition between two biological communities—they support hybridised populations and dynamic exchanges. Maintenance practices in these areas can be reimagined as ecological stewardship, where probiotic cleaning (Ramos and Frantz, 2023) and microbial replenishment are part of routine care rather than reactive sanitation.

Holobiontic architecture, then, is not a metaphorical dream but a material strategy, which designs for the biological processes that unfold across surfaces and within structures. Microbes mineralize carbon, lichens modulate air quality, and biofilms generate redox gradients that can be harnessed for sensing or energy production. The reef analogy becomes operational: architecture is both scaffold and substrate for life.

2.2 Selective Pressures and the Exposome

Having examined how material surfaces shape microbial communities, it is equally important to consider the broader environmental conditions that influence microbial life within and around buildings. Microbes, as living organisms, are subject to selective pressures arising from their surroundings. Ranging from temperature and humidity to air quality, occupant behaviour, and cleaning practices—these pressures collectively form what is known as the exposome: the totality of environmental exposures an organism experiences over its lifetime (Balcells et al., 2024).

In the built environment, the exposome plays a critical role in determining which microbial species persist, how they function, and the nature of their interactions with human hosts. These conditions do not merely influence microbial presence; they shape microbial behaviour, succession, and adaptation—introducing the possibility of evolutionary change within architectural contexts. According to the *hologenome theory*, natural selection acts on the combined genetic material of hosts and their associated microbiota (Morris, 2018) enabling buildings and their microbial communities form co-evolving systems, responding together to environmental stimuli over time. Although human occupation is brief on evolutionary timescales, the materials we leave behind—such as concrete, plastics, and composites—persist as colonisable substrates that continue to support microbial life long after their original use has ended. In this sense, buildings become long-term scaffolds for microbial succession, carrying forward biological potential into futures that may no longer include human inhabitants.

This perspective reframes architecture as a time-based, living archive—one that decentres human occupation as the locus of all events, and records ecological trajectories, as well as cultural and material histories. As human-associated microbiomes fade, environmental communities may take their place, gradually reshaping the building's microbial landscape. The structure itself continues as a host even when the human residents are gone, its surfaces and geometries offering niches for colonisation, attachment, and adaptation. Through the lens of the hologenome and the exposome, holobiontic architecture offers a framework for understanding how spatial, biological, and cultural change emerges from the entanglement of life forms and their environments—across generations, and potentially beyond human settlement.

2.3 A Holobiontic Material Practice

Holobiontic architecture is shaped by the metabolic realities of materials in space and time, offering a design strategy to create structures that are ecologically embedded, temporally attuned, and metabolically active. Unlike frameworks such as actor-network theory (Latour, 1996), which describe the distribution of agency across networks, holobiontic design is grounded in the tangible, biochemical interactions between materials and microbes. Aligning with Donna Haraway's concept of *sympoiesis*—"making-with" other species (2019)—it adds a material and temporal dimension to this relational thinking. For instance, limestone favours colonisation by acidophilic bacteria, while cedar's tannins inhibit fungal growth. These interactions are not incidental; by manipulating surface roughness, moisture retention, and light exposure, architects can actively shape the selection and growth of microbial ecologies. What might once have been dismissed as contamination—such as algal streaks or microbial patinas—can now be understood as signs of ecological function. These visible traces reflect the building's ongoing interaction with its environment, offering insight into its microecological health. Over time, they may even serve as environmental records, encoding shifts in humidity, pollution levels, or microbial composition.

In this context, holobiointic architecture becomes a dynamic substrate for co-evolution. Cracks in concrete host pioneer species; HVAC systems distribute airborne microbes that metabolize indoor pollutants; and material degradation gives rise to new habitats. These processes unfold both in the present and across extended timescales, as buildings persist beyond human occupancy and continue to support microbial life. Architecture, in this view, is not simply constructed; it is cultivated, inhabited, and inherited by multiple forms of life across generations.

3. From Holobiont to Bio-Baroque: Ornament as Ecological Interface

As more architects experiment with designing surfaces that support microbial life, a distinct aesthetic is beginning to emerge. This aesthetic is not incidental, but the product of a shared vision, a growing understanding of microbial ecologies, and the use of advanced fabrication technologies. Informed by what microbes need to thrive—such as moisture, texture, and chemical compatibility—designers are crafting surfaces that are both expressive and ecologically purposeful. This emerging language of form, which I refer to as *eco-ornamentation*, reflects a shift in architectural thinking: from surface as decoration to surface as habitat. It marks a convergence of ecological intelligence, material science, and digital craft, giving rise to a new kind of ornamentation that is metabolically active and biologically informed.

Unlike the visual excesses of the 17th-century Baroque, Bio-Baroque surfaces are dynamic, reflecting ongoing biological processes (Sanjurjo-Sánchez et al., 2024; Ortega-Morales et al., 2025). A mould bloom on a ceiling may indicate elevated humidity, while Streptomyces-derived pigments can signal soil-like microenvironments. These phenomena are not just visual—they are diagnostic, offering insight into a building's microecological state. This approach also redefines maintenance. Managing a Bio-Baroque surface involves practices akin to microbial cultivation: applying bacteriophage treatments to suppress pathogens or using probiotics to encourage beneficial colonisation (Al-Fakhrany and Elekhnawy, 2024; Ramos and Frantz, 2023). In this context, architects collaborate with microbiologists and materials scientists to guide ecological succession, shaping stable, health-promoting microbial communities through design.

Despite its ecological potential, the Bio-Baroque approach faces persistent cultural and perceptual resistance. While natural colonisation is often celebrated in landscape design, similar microbial growth in architectural contexts is frequently interpreted as neglect or contamination. Lichen-covered façades and biofilm-streaked walls are typically viewed as maintenance failures rather than indicators of ecological function. This response reflects the enduring influence of hygiene-oriented design ideologies, even as contemporary science increasingly challenges the sterility paradigm.

3.1 Material Tensions

The dynamic nature of biologically active surfaces introduces practical challenges. Unlike traditional ornamentation, which remains materially stable over time, Bio-Baroque surfaces respond to environmental fluctuations. A façade designed to support cyanobacterial growth may change colour with seasonal humidity, potentially conflicting with conventional expectations of permanence and visual consistency. While weathering in stone is often accepted, similar changes in microbial pigmentation may be perceived as degradation.

There is also the risk of unintended colonisation. As with coral reefs that experience algal overgrowth under nutrient stress, Bio-Baroque surfaces may support undesirable microbial communities if environmental conditions change. For example, a façade intended to host nitrogen-fixing bacteria might instead support acid-producing strains under pollution stress, accelerating material decay. Addressing these risks requires careful material selection, environmental calibration, and ongoing monitoring—potentially through embedded biosensors, microbiome sampling, or automated diagnostics capable of distinguishing beneficial from harmful microbial activity.

3.2 Cultural Resistance

Beyond material and ecological considerations, Western architectural traditions associate microbial flourishing with disorder, decay, or neglect. The enduring modernist preference for clean lines, smooth surfaces, and visual uniformity reinforces a perception of sterility as a marker of quality and control. Even when microbial colonisation is intentional and beneficial, terms such as “biofilm” or “fungal growth” often provoke discomfort, while more neutral alternatives like “living surface” risk obscuring the biological specificity and ecological function of such designs.

However, this discomfort is not universal. The enduring popularity of the Japanese garden offers a compelling counterpoint. In this tradition, living surfaces—particularly moss and lichen—are not only accepted but revered (Oishi, 2022). Moss appears in the Japanese national anthem as a symbol of longevity and quiet persistence, and its presence in gardens is seen as a sign of maturity and ecological harmony. Unlike the Bio-Baroque, which uses digital fabrication and engineered textures to guide microbial colonisation, the Japanese garden relies on environmental conditions—shade, moisture, and time—to invite life without imposing form (Table 3). This approach, grounded in the aesthetic philosophy of wabi-sabi, values impermanence, asymmetry, and the beauty of natural imperfection. Surfaces are not curated canvases but ecological records, shaped by the slow accumulation of organic processes.

Aspect	Bio-Baroque	Japanese Wabi-Sabi
Design Approach	Engineered colonisation (3D-printed textures, rapid manufacturing etc.) to optimise cultivation	Curated conditions (shade/moisture)
Temporality	Predictive models guide succession	Uncontrolled, slow natural processes
Ornament Role	Reflects mode of production and the slow flow of elements (air, water, accumulation of dirt) across the material surface	Ephemeral record of time.
Functionality	Functional metabolic interface directed toward specific aims	Related to biological niche
Location	Exterior or Interior	Exterior
Microbial Agency	Directed through material design	Spontaneous emergence
Cultural Roots	Western biotech innovation	Zen Buddhist
Set-up (curation of organisms)	Passive and active microbial gardening dependant on intended function	Minimal intervention
Maintenance	Minimal intervention unless probiotic, then probiotic hygiene protocols	Minimal intervention

Table 3. Comparison between Bio-Baroque and Wabi-Sabi

While the Bio-Baroque and the Japanese garden differ in method, they share the view that microbial life can enhance human well-being, sensory experience, and ecological connection. Both styles exert forms of control—one through design intervention, the other through environmental curation—but each recognises the value of cohabitation. The Japanese garden reminds us that holobiontic architecture need not always be expressive or ornate. It can also be quiet, patient, and attuned to the intelligence of natural systems.

The success of Bio-Baroque will depend on technical and material innovation as well as the ability to communicate its principles in ways that resonate across aesthetic traditions. Making microbial life visible, interpretable, and culturally legible is essential to altering public perception. In this way, the Bio-Baroque becomes more than a design strategy—it becomes a framework for negotiated coexistence, where architecture mediates between human needs, microbial ecologies, and diverse cultural values in the shared space of the built environment.

4. Bio-Baroque's Hidden Counterpart: The Electroactive Underground

As architecture enters the age of eco-ornamentation, a new frontier is emerging at the interface: microbial intelligence**.** Microbes are not merely agents of metabolism, or contamination, but computational actors—capable of sensing, processing, and responding to environmental stimuli. In this context, microbes function as site-embedded microprocessors, forming the basis of "smart embodied" forms of computation (Armstrong, 2024a), or *unconventional computers* (Stepney, 2025; Armstrong, 2025), such as slime-mould computing (Tero et al., 2010), and hybrid bio-digital systems (You et al., 2021). Operating through a range of metabolisms, the design of interfaces that enable humans to influence these biofactories, can transform how buildings operate and interact with their environments.

4.1 Aerobic covers

Bioreceptive and probiotic surfaces are typically associated with aerobic exteriors—gardened *Bacillus* colonies, proliferative biofilms, green walls, moss façades, and lichen-covered stone. Aerobic biofilms offer significant potential in architectural design for their biocatalytic capabilities and for enhancing the physical resilience of building surfaces. By engineering targeted microniches, microbial communities can transform passive substrates into active, self-regulating systems. These biofilms perform functions—including redox reactions, mineral transformations, and gas exchange—that contribute to surface protection, pollutant degradation, and environmental adaptation (Sanjurjo-Sánchez et al., 2024).

While microbial colonisation in building conservation remains debated—particularly regarding biofouling and material degradation (Komar et al., 2023; Rotondi et al., 2024)—interest is growing in microbial strategies that support bioconservation. This includes using biological agents as sustainable alternatives to conventional restoration methods (Ortega-Morales et al., 2025). In conservation science, microbial biocatalysis is typically applied in two domains: remediation, involving microbial breakdown of pollutants or damage, and consolidation, where biological processes strengthen vulnerable materials. A well-established example is Microbially Induced Calcite Precipitation (MICP), which reinforces calcium-rich substrates such as limestone and marble, improving surface stability and resistance to weathering (Ortega-Morales, 2025; Sanjurjo-Sánchez et al., 2024).

To scale these processes, engineered coatings—"living paints"—are being developed to support microbial viability and adhesion. These coatings use water-based polymer emulsions (latexes) to deliver concentrated microbial cultures to surfaces, enabling continuous metabolic activity (Veeger et al., 2025; In-na et al., 2022b). Cyanobacteria, for example, precipitate calcium carbonate ($CaCO_3$) by consuming atmospheric CO_2, turning façades into carbon capture systems (Sanjurjo-Sánchez et al., 2024; Reinhardt et al., 2023), especially effective on high-emission materials like concrete (Wang et al., 2025).

Other innovations include algae-based biogels that absorb heavy metals from wastewater (Dubey et al., 2023) and immobilised *Bacillus simplex* in acrylic films that precipitate $CaCO_3$ to fill microcracks without external pH adjustment (Ortega-Morales et al., 2025; Jennings et al., 2024). "Lichen mimic" biocomposites are also being developed to retain cyanobacterial cells long-term, achieving CO_2 absorption rates 14–20 times higher than controls over 12 weeks without added nutrients (In-na et al., 2022b).

To support the design and optimisation of these living systems, new digital toolsets are emerging. While conventional tools like *Building Information Modelling* (BIM) and *Computer-Aided Design* (CAD) simulate material behaviour under physical conditions (Thomsen, 2022), they cannot model biological dynamics. Biotechnologically informed platforms now simulate microbial metabolism, ecological interactions, and spatial distribution (Wong et al., 2024; Wang et al., 2023a). Computational frameworks such as Genome-scale Metabolic Models (GEMs) and COnstraint-Based Reconstruction and Analysis (COBRA) optimise microbial consortia for CO_2 fixation or pollutant degradation (Nogales et al., 2022).

Advanced biology tools further enhance this capability through spatial analysis. RAINBOW-seq reveals metabolic activity in nutrient-deprived biofilm regions (Wang et al., 2023b), while large-area Atomic Force Microscopy (AFM) maps biofilm dynamics at the millimetre scale (Millan-Solsona et al., 2025). For fungi, 3D growth models now integrate environmental fluctuations and metabolic pathways (Carlström et al., 2024). Navigating the complexity of these systems requires computational methods that incorporate feature engineering, dimensionality reduction, and signal translation—converting high-dimensional biological responses into actionable design parameters. Early prototypes of living bioelectronic skins, embedded with fungal or bacterial

sensors, demonstrate how such systems can monitor structural loads, air quality, or temperature while simultaneously processing pollutants (Adamatzky et al., 2022).
Together, these developments position aerobic biofilms as biocatalytic agents and integral components of a new architectural materiality—responsive, regenerative, and ecologically embedded.

4.2 Anaerobic biofilms

While much attention is given to the aerobic microbes colonising building surfaces, there is further untapped potential in the anaerobic, involuted interiors of buildings, particularly within waste streams. Here, electroactive biofilms (EABs) colonize conductive surfaces such as anodes in Bioelectrical Systems (BES)**.** These systems, including microbial fuel cells (MFCs) and microbial electrolysis cells (MECs), use the metabolic activity of electroactive microbes (EAMs) like *Geobacter*, *Shewanella*, and certain fungi to perform extracellular electron transfer (EET). In doing so, they convert organic waste into clean water, valuable biomolecules, and bioelectricity—a form of microbial feedback that can be captured and interpreted at biodigital interfaces (You et al., 2022; Naha et al., 2023; Leicester et al., 2023; Li et al., 2023; Reyes et al., 2024; Hemdan et al., 2023; Perchikov et al., 2024; You et al., 2021). In this context, the anode becomes a highly specialized bioreceptive surface—its performance shaped by surface area, porosity, material composition, and microbial co-culturing strategies (Pamintuan et al., 2024; Ma et al., 2023; Ajit et al., 2024; Yuan et al., 2023; Nguyen et al., 2024). Reactor geometry and the use of biomass-derived biocatalysts further influence the efficiency and specificity of microbial activity. The bioelectrical signals produced by the bioanode are not just byproducts—they are data streams. When integrated with electronic sensors and machine learning algorithms, they enable real-time environmental sensing and adaptive system control. The challenge lies in decoding these signals, which are often the summation of multiple metabolic events. One promising approach is to spatialise microbial communities according to their metabolic functions, allowing for more precise calibration of signal-to-event relationships. These variables can be optimized through machine learning, creating closed feedback loops between microbial metabolism and architectural response (Goap et al., 2018).

This convergence of biology and computation has significant implications for energy-insecure and resource constrained communities. In rural regions of Africa, for example, low-cost BES systems offer decentralized alternatives to grid electricity, converting household organic waste into power while reducing reliance on polluting fuels (Fuku et al., 2025; Chimoio, 2025). But the potential extends beyond energy: engineered BES can also produce surfactants, enzymes, and rhamnolipids, enabling off-grid biorefineries that turn waste into valuable resources (Reyes et al., 2024; Singh et al., 2024; Sharma et al., 2025; Khabeil et al., 2025). In urban contexts, similar systems could be embedded into adaptive buildings that metabolize CO_2 into biofuels (In-na et al., 2022a). These hybrid systems embody a new form of architectural intelligence—situated, responsive, and living. As microbial data informs AI ontologies, buildings begin to learn not only from human input, but from the metabolic rhythms of the microbial world.

4.3 Towards Biologically 'Smart' Architectures

The incorporation of engineered materials and modifiable microbial metabolisms into buildings establishes the foundations for biologically 'smart' architecture. This redefines intelligence as the embedded metabolic capacity of living systems to sense, respond, and transform their environments, which can be augmented and understood via digital media. In this model, microbial communities function as dynamic, site-sensitive layers of coordinated biochemical activity. Rather than simply producing data, these biofilms actively participate in building metabolism—producing and denaturing biomolecules, regulating gas exchange, and catalysing mineral transformations. Their intelligence lies in their unconventional computing abilities (Stepney, 2025) and ecological embeddedness: they are attuned to local conditions, responsive to environmental change, and capable of sustaining material and biological cycles over time.

This form of intelligence is not abstracted into graphical displays on remote servers or dashboards. It is situated in the material fabric of the building—on façades, in ventilation systems, and within wastewater infrastructure—where microbial consortia perform protective, regenerative, and communicative functions. Biologically 'smart' buildings reduce environmental impact by actively contributing to the environments they inhabit, enhancing air quality, stabilising surfaces, and remediating pollutants. In this sense, the building becomes a site of metabolic gardening, where microbial life is cultivated through mutual benefit between occupants and microcolonies.

The development of applications such as artificial lichens that metabolise airborne toxins (In-na et al., 2021) or microbial fuel cells that detect and neutralise waterborne pathogens (Pasternak, Greenman and Ieropoulos,

2019) are establishing the potential of these systems. Their significance lies both in their functionality, and in their capacity to transform architecture into a co-evolving interface—responsive, adaptive, and ecologically situated. These persuadable systems (Stepney, 2025; Armstrong, 2025) host microbes as trusted collaborators in the design of more liveable, regenerative, resilient futures.

5. From Eradication to Negotiation: A New Immunological Paradigm

As microbes are increasingly recognised as essential contributors to human and environmental health, holobiontic architecture reframes immunity as negotiation, not eradication. This change draws on Polly Matzinger's Danger Theory (Palazón et al., 2008), which reconceptualises immune response as a context-sensitive reaction to actual harm, rather than a binary distinction between "self" and "non-self." This approach resonates with feminist critiques of immunity that reject militaristic metaphors in favour of relational, embodied, and situated understandings of health (Haraway, 2019). Like the gut lining, architectural surfaces regulate what enters, settles, and thrives—not through exclusion, but through calibrated coexistence. Hygiene becomes a form of microbial diplomacy: a ritual of care that cultivates ecological balance rather than enforcing sterility.

In architectural terms, this model challenges the modernist paradigm of hygiene—characterised by sealed surfaces, biocidal materials, and sterilisation protocols—which has been linked to disrupted indoor microbiomes and rising rates of immune dysfunction (Fu et al., 2021). Holobiontic design instead promotes selective tolerance, where surfaces are engineered to support beneficial microbial communities while suppressing pathogenic ones. This immunological logic extends beyond individual surfaces to encompass entire building systems. Architectural features such as moss-integrated ventilation (King, 2014) and microbial "airlocks" at thresholds mediate microbial exchange, supporting immune modulation through controlled exposure. Bioelectrochemical systems embedded in wastewater infrastructure—such as microbial fuel cells—serve dual roles as metabolic processors and biosensors, detecting pathogen surges via voltage fluctuations and generating real-time data that can inform adaptive responses (Pasternak, Greenman and Ieropoulos, 2019). Maintenance practices evolve accordingly, involving probiotic cleaning (Ramos and Frantz, 2023) and spatial strategies that manage microbial territories through ecological zoning.

Crucially, these systems are not isolated. A single holobiontically-designed building becomes part of a larger microbial network—its surfaces, airflows, and waste streams contributing to a distributed ecological infrastructure. Through coordinated design, these operations can be networked into neighbourhood- and city-scale systems that strategically activate microbial processes across spatial and temporal scales. This is exemplified by speculative models like *Immunological City* (Armstrong, 2024b), where microbial fuel cells embedded in urban waste streams function as biosensing nodes within a decentralized immune system. In this vision, microbes are integrated into the fabric of buildings and cities to enhance human and ecological resilience. Through their biodiversity, regenerative capacity, and metabolic potency, they serve as both early warning systems and first-line defenses against the micro-scale environmental symptoms of climate change.

Ultimately, holobiontic architecture positions immunity as a design principle that scales—from the body to the building, and from the building to the city. It invites a transition from reactive exclusion to evidence-based negotiation, where coexistence is continually recalibrated to support collective thriving. Through microbial stewardship, ecological attunement, and multispecies collaboration, we begin to imagine cities that are not only intelligent but compassionate—being designed for humans and the microbial worlds that sustain us.

6. Toward a Protocol for Cohabitation

Holobiontic architecture reimagines buildings as *meta-holobionts*—living systems shaped by microbial stewardship, dynamic material performance, and multispecies interdependence. Eco-ornamentation, exemplified by the Bio-Baroque, integrates microbial life into the expressive and metabolic fabric of architecture, moving beyond decoration toward ecological function. But this paradigm demands more than technical innovation—it calls for a cultural shift: one that redefines ornament, reconditions perception, and reframes hygiene as ecological diplomacy. Key questions remain: How do we balance microbial autonomy with human health? How do we prevent aesthetic trivialisation? And how do we build ethical frameworks for multispecies design? Still, the direction is clear. In learning to live with microbes—through architecture that senses, adapts, and cohabits—we may also learn to live more responsibly with each other. Like the reef, the building becomes a site of negotiated coexistence: resilient not through control, but through collaboration.

Figures and Tables

Table 1. Comparative Table: Surface Typologies in Holobiontic Architecture
Table 2. Three principles of holobiontic architectural design
Table 3. Comparison between Bio-Baroque and Wabi-Sabi
Figure 1. Architecture as Meta-Holobiont: From Human Microbiome to Urban Ecosystem

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