Designing Biodiverse High-Rise Façade Microbiomes for Healthy Urban Environments

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Abstract

This study takes a first step towards exploring the microbiomes of existing building façades in Suzhou, China, informing proposals for alternative design approaches to architectural façade elements capable of hosting desirable microbial biodiversity to benefit human health, as well as the overall quality of urban environments. Results of this study are relevant to the design of high-rise buildings as they call for comprehensive approaches to sustainable design of building surfaces beyond energy and carbon considerations.

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Introduction

Over the past decade, research in medicine and environmental biology has increasingly drawn attention to the interactions between microbial communities present in human living environments and human health. Recent related studies can be found across a broad range of fields, from biology to environmental science to materials studies, ecology, medicine and architecture. In response, architecture and related disciplines are challenged to address issues of healthy living with new types of design approaches, extending the scope of building design to include non-human inhabitants as part of post-human-centric design strategies (Roudavski 2020; Mills et al. 2019). An increasing number of recent studies draws attention to close links between the human microbiome, immune system and health (Hanski et al. 2012). Early global studies mapping urban microbiomes, as conducted by the MetaSUB International Consortium (Danko et al. 2021) have shown that urban environments across the world develop specific microbial biomes, which in turn have direct impacts on their urban inhabitants through constant microbial exchange.

Urban planning and architecture are only beginning to take notice of this new design dimension. When developing sustainable visions of future constructed environments, we predict that considerations relating to human health and well-being, within the broader scope of urban ecology, will increasingly become central to constructed environments. As such, microbial biodiversity should be maintained and supported as part of the general concern of maintaining biodiversity in our environments across multiple scales.

Human microbiomes depend on close exchanges with microbial communities in our environments. In this context, architectural design, layout and especially ventilation are key factors in determining the microbiome of buildings. Indoor microbiome diversity is thus closely linked to airborne exchanges with external microbial communities—which is readily available in smaller-scale buildings close to natural biodiversity in surrounding environments. However, it is not clear how increasingly dense urban environments with shrinking reservoirs of natural biodiversity will facilitate similarly healthy environments for their occupants. Building façades could play a central role as a source of microbial diversity in immediate proximity to inhabited spaces. This is especially relevant for dense urban environments, where less and less land is dedicated to microbially diverse green

Figure 1. The Central Building of Xi'an Jiaotong-Liverpool University is the research project study site.

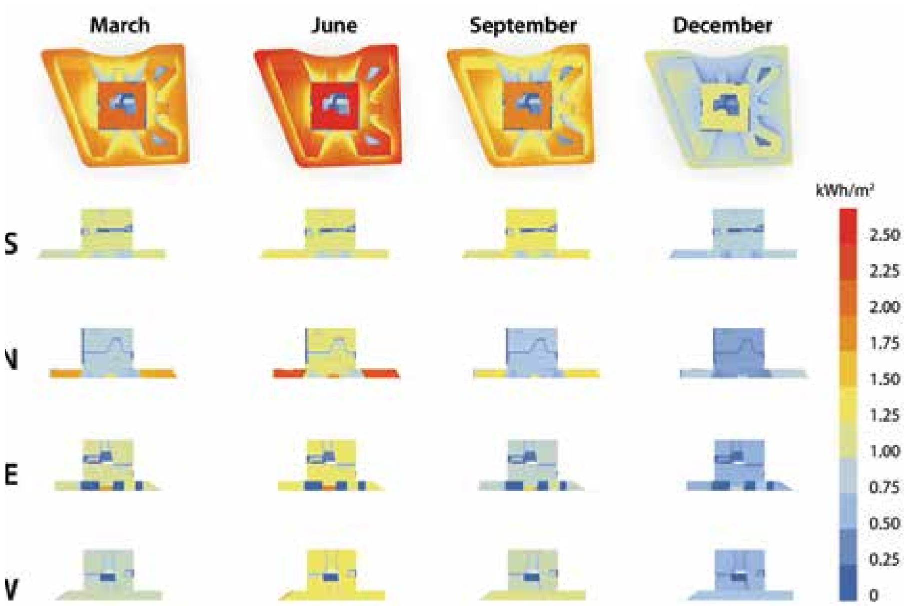


Figure 2. Solar radiation received by the four main façades of the Central Building.

space (Flies et. al. 2017), and where microbial biodiversity is increasingly lost.

This study focuses specifically on the microbial biodiversity of building façades, linking an empirical study of existing façade microbiomes with architectural design of new façade proposals. The research focuses on the analysis of microbial DNA sampled from an existing medium-rise building of 13 floors, located on the campus of Xi'an Jiaotong-Liverpool University in Suzhou, China. Based on insights gained from the first empirical phase of the study, the paper implements several related design strategies and proposes a new façade design approach.

Research Method

The main research question investigated in this project is: How can exterior building façades be designed to encourage and support biodiversity in microbial communities? Existing studies have not examined façade microbiomes comprehensively yet. Moreover, much work in the field has been concerned with limiting or eliminating growth of microbes on façades, often related to the protection of historical façades, to maintain building aesthetics or to reduce maintenance cost. This study sets out to generate basic understanding of building façade microbiomes with a different aim, seeking to inform the design of future living façades that can support human health and well-being as part of a biodiverse building ecology.

The focus of the project was the Central Building of Xi'an Jiaotong-Liverpool University (XJTLU) in Suzhou, China, completed in 2013 (see Figure 1).

The local climate of Suzhou is characterized by humid, hot summers and cool winters with occasional frost. The general sun radiation received by the building throughout the year, as illustrated in Figure 2, generates four distinct climatic conditions on each side of the building.

Phase 1: Sampling and Analysis, April–July 2021

The first stage of the project was conducted as an exploratory and small-scale metagenomic study of different materials found throughout the building. A set of 28 samples was taken from the exterior of the Central Building at various locations and elevations and analyzed for both prokaryotic (including plants/fungi) and bacterial DNA (16SRNA and 18SRNA, 56 analyses in all). In this process, to obtain a sample breadth as broad in scope as possible, we did not restrict the sampling to vertical surfaces. Results offer insights into the presence and growth of microorganisms, bacteria and eukaryotic taxa on the surfaces of the analyzed building. DNA samples were evaluated by a professional external company. Results build on an initial study by Herr and Duan (2020), which mapped microbiomes across different building surfaces.

Phase 2: Design, April–October 2021

The main design phase of the project was based on results of the analysis of the

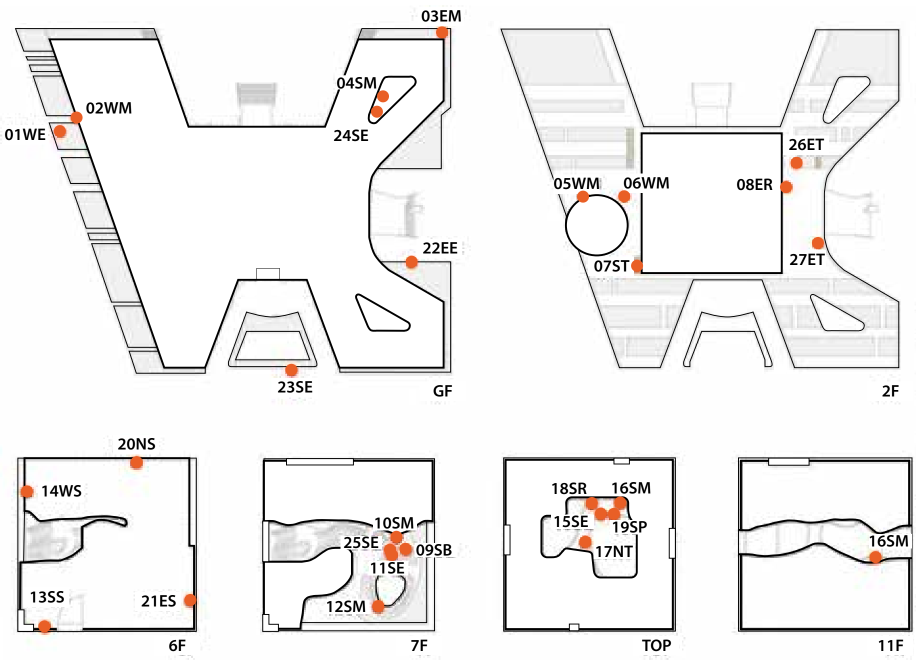


Figure 3. Swab sampling sites mapped on the plans of the XJTLU Central Building.

Sample	Number	OTUs	Shannon	Chao	Ace	Simpson	Shannon	Coverage
01WE	30051.0	1465.0	5.70	1534.91	1527.70	0.01	0.78	0.99
06WE	28420.0	1293.0	5.91	1463.08	1430.66	7.90E-03	0.82	0.99
09SB	43516.0	247.0	3.11	251.50	249.67	0.13	0.56	1.00
11SE	29935.0	1106.0	5.65	1151.07	1140.10	0.02	0.81	1.00
15SE	24592.0	1521.0	5.97	1844.00	1744.78	9.60E-03	0.81	0.99
17NT	40256.0	203.0	1.79	213.04	212.35	0.30	0.34	1.00
19SP	41989.0	518.0	4.12	528.12	524.56	0.06	0.66	1.00
20NS	41651.0	1063.0	5.63	1121.24	1076.12	0.02	0.81	1.00
21ES	39385.0	525.0	4.39	536.14	529.05	0.06	0.70	1.00
22EE	41331.0	1546.0	5.67	1842.03	1779.17	0.02	0.77	0.99
23SE	43121.0	1604.0	5.99	1891.19	1818.50	8.60E-03	0.81	0.99
24SE	52575.0	1721.0	6.10	1963.61	1907.56	6.00E-03	0.82	0.99
25SE	43813.0	1588.0	5.60	1804.75	1784.60	0.02	0.76	0.99
26ET	45792.0	377.0	1.94	569.52	695.04	0.43	0.33	1.00

Table 1. Surface swab samples analyzed for prokaryotes (16s RNA) and characterization. OTUs (Operational Taxonomic Units) measures abundance; the Shannon index measures diversity.

samples taken in the first phase of the project. The project team developed detailed designs of surface patterns, materials and strategies for sunlight exposure for the new façade design proposals. Four overall façade design proposals were generated, three of these in a one-week design workshop involving additional XJTLU architecture students. While the workshop had a slightly broader scope and focused on ecological design and biodiversity, the outcomes reflect the evolving design thinking of the project team. The final design proposal is articulated and presented in the following sections. Scale models were produced to test and verify design ideas at the scale of 1:10. In addition, a set of 12 full-scale prototype façade panels supporting microbial biodiversity was fabricated at 1:1 scale.

Environmental DNA Samples

This project involves a variety of environmental sampling strategies to understand microbial communities across different substrates, from swabs to solid soil samples. The challenging aspect in taking various types of environmental samples is the resulting lack of quantitatively comparable data. This type of sampling strategy is rarely used, as it does not afford standardization and comparison in terms of directly comparable sampling sizes. For the purposes of this study, however, to understand the invisible microbial dimension present on building surfaces, a qualitative insight into the microbial diversity present on the examined building can generate a new perspective for architecture and still support the design of surfaces from new perspectives. Figure 3 illustrates sampling site locations on the building plan.

16s RNA Analysis

The team sent 28 samples to the 16s RNA analysis stage, which is used to identify taxa of prokaryotes (bacteria). Table 1 features those samples in the set containing the most biodiversity. Almost all samples containing soil were included, along with a variety of materials, including different types of metal, timber and plastic. Unsurprisingly, most of the samples containing too little variation were taken from metal cladding sheets used on building façades, which are engineered to resist bio-colonization. The columns show, from left to right, the sample name, Operational Taxonomic Unit (OTU), a DNA component unit count indicating the number of identified genetic units; and the Shannon diversity index, indicating alpha biodiversity. Both indices can be used to compare materials. The overview clearly shows that metal and plastic samples (09SB, 19SP) are not very hospitable to microbial communities in comparison to natural materials such as timber (where it depends on the surface treatment) or soil samples, no matter to which orientation the latter are exposed.

Figure 4 offers a more intuitively understandable overview of microbial

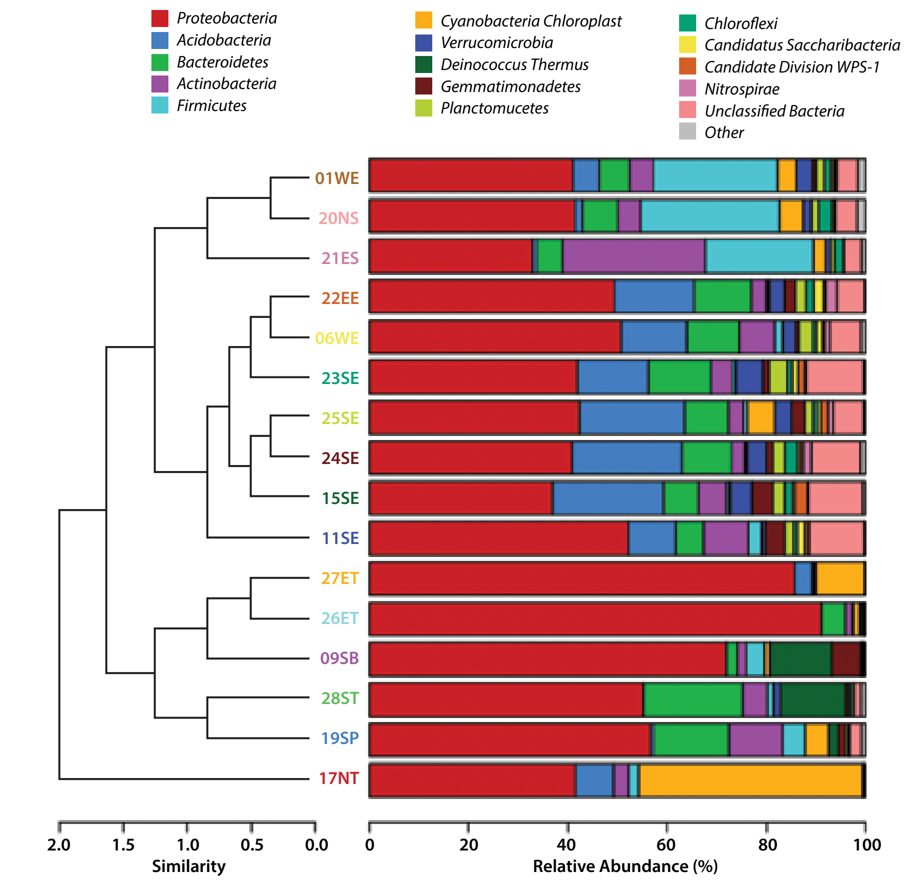
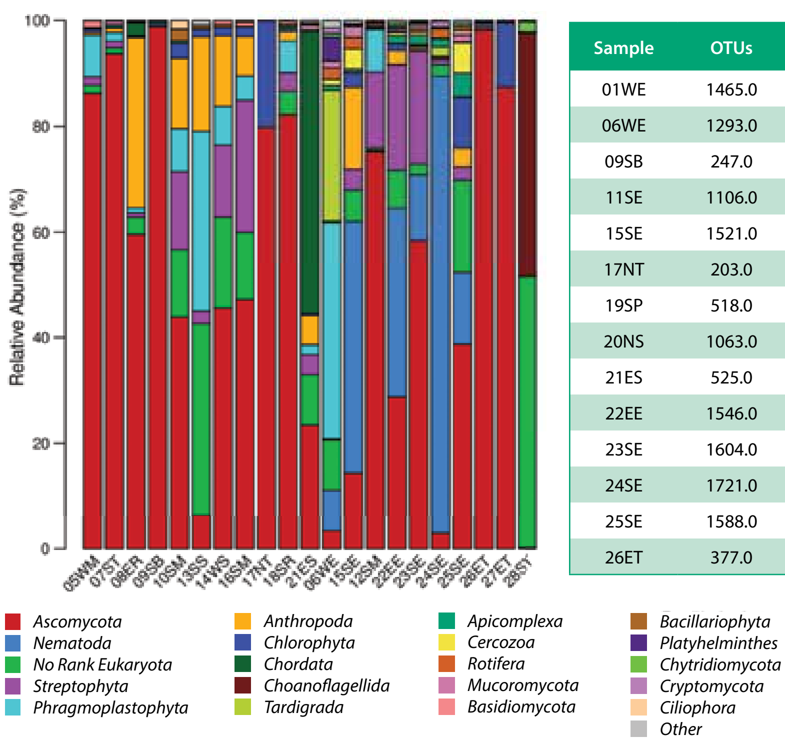


Figure 4. Grouped graph illustrating similarity between samples, while also showing relative abundance of microbial taxa in relation to the sample size.



Sample	OTUs	Shannon
01WE	1465.0	5.70
06WE	1293.0	5.91
09SB	247.0	3.11
11SE	1106.0	5.65
15SE	1521.0	5.97
17NT	203.0	1.79
19SP	518.0	4.12
20NS	1063.0	5.63
21ES	525.0	4.39
22EE	1546.0	5.67
23SE	1604.0	5.99
24SE	1721.0	6.10
25SE	1588.0	5.60
26ET	377.0	1.94

Figure 5. Relative abundance (left) and diversity (right) of 18s RNA eukaryotes in each sample taken from the Central Building.

diversity present across all samples through relative abundance measure (right) while also showing similarity through the relational graph to the left. While the graph does not show absolute abundance in terms of OTU numbers, the colored graph illustrates how different communities of microbes are composed of different phyla of microbes. It clearly shows how some samples have similar patterns, despite being taken from different floors, due to their substrates. Samples 22EE–22SE, for example, are all soil samples. From this overview, it can be observed that soil will generate a certain type of microbial community.

Sample 21ES, meanwhile, was taken from an exterior steel façade element and features a unique combination of DNA sequences, indicating a different chemical environment supporting specific microbes, most notably the phylum of Firmicutes. Samples 26ET and 27ET were obtained from timber surfaces, one horizontal and one vertical. They show the least variety in their microbial communities, which can likely be attributed to the varnished surface of the timber, which does not seem to lend itself to microbial colonization.

18s RNA Analysis

All 28 initially collected samples were also submitted for 18s RNA analysis, which is used to identify eukaryotic microorganisms such as fungi and algae, or animal cells in environmental samples. The overview in Figure 5 (left) shows eukaryotic biodiversity in terms of relative abundance within each sample. Most notably, eukaryotic diversity is much more varied throughout the overall sample than bacterial community variety, and seems comparatively sensitive to environmental conditions. Samples 07ST and 26ET, for example, featuring very reduced diversity, were both obtained from varnished timber exterior floor surfaces. One possible explanation for this may be that the substrate material was chemically treated to prevent the growth of fungi. Samples 13SS and 06WE, taken from a metal façade shading shelf and a soil sample, respectively, were the most diverse. One common pattern among the eukaryote communities

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seems to be that they become more diverse in more shaded, humid conditions. Likewise, at least some eukaryotes seem to thrive less when exposed directly to sunlight and dryness, such as in sample 09SB, which was taken from a sunlight-exposed corroded steel bench.

Analysis of DNA Samples

This mini-metagenomic study offers a first insight into the qualities of microbial communities that can be expected to be present in the specific geographic location and climatic context of Suzhou, China. Knowledge of microbial communities, and in particular, their functions, is far from complete. In the above figures, many graphs contain a category of "unclassified" or "other" taxa. In this context, the insight that every surface in a building, including the façades, is densely populated by microbes, may be an uncomfortable thought, as there are not many experiences or guidelines in design-related fields indicating how designers could conceptualize and address this invisible dimension of buildings. How, then, can we respond to this new perspective?

In this study, we take a systemic, ecological approach. We assume that biodiversity renders a microbial community more stable over time, such that it can offer certain "ecosystem services" to human occupants. In this conception of desirable microbial communities, biodiversity would serve as a balancing mechanism through which potentially pathogenic microorganisms are managed through competition with other, less pathogenic microorganisms. In terms of architectural impact, several insights can be derived from the analysis.

While microbial colonization of surfaces on building façades typically takes place via aerial vectors, microbial communities developing on specific surfaces seem to depend significantly on a few key factors. Man-made inorganic materials are only populated by a limited number of microorganism taxa. Choosing materials more friendly to and supportive of bio-colonization will foster biodiversity by allowing microorganisms to propagate. Extended direct sun exposure reduced biodiversity in microbial communities, in particular. Humidity seems to be less important in microbial propagation than sunlight. The full effect of water on microbial communities in the samples taken in this study is unclear, as for example, soils in samples 24SE and 25SE showed similar bacterial biodiversity patterns, despite different levels of water availability.

While we were advised by an experienced ecologist that microbial communities at a given location are likely "coincidental" and entirely dependent on environment only, we could clearly see differences in microbial communities depending on the environmental factors outlined above. We identified geometry as one of the factors modulating environmental conditions for microbial communities at the very small architectural scale, particularly around sun exposure. From a design perspective, this is an interesting opportunity to develop façade surface patterns that provide carefully constructed opportunities for biodiversity at the microbial scale.

Façade materials have a key influence on microbial community composition. Industrially produced and processed materials such as plastics, treated timber and glass do not seem to support diversity in microbial communities well, even long after the materials have been installed, and some surfaces may even have toxic effects on their environments. This is not a surprise, since materials engineered for external façade use are designed to repel growth for maintenance reasons. The diversity and "health" of façade microbiomes can thus be understood a general indicator for urban health and well-being.

Microbial biodiversity may best be thought of along ecological principles. Microbial communities will attempt to colonize all building surfaces through a variety of vectors, so designing surfaces with suitable material selection and geometric composition strategies can take a "passive design" approach to make sure only desirable microbial communities can be found on a given building façade. To develop this design approach, it will be necessary to develop broader knowledge about suitable substrates and the likely microbial communities that can be expected to develop on these substrates.

Findings Resulting from Sample Analysis

Based on the analysis of empirical data collected through DNA analysis, some initial conclusions could be made:

Building materials have significant influence on façade microbiomes, determining both the composition and the diversity of microbial communities. While inorganic and processed materials such as metals and glass are found to discourage bio-colonization of surfaces, soil seems to be the most supportive substrate material to create biodiverse microbial communities. While material texture and porosity may play a role in microbial colonization, their specific effects could not be determined in detail, due to the limited number of samples.

Microbial biodiversity in samples taken for this study does not show significant differences with respect to the sampling site's elevation above ground. While the height of the building analyzed for this study was limited to 13 floors, we find that material characteristics, sun, and possibly water exposure are stronger predictors of microbial propagation on façade surfaces than elevation above ground *per se*. It is unclear how proximity among specific microbial communities within one building, or between a building and its urban context, influences microbial community composition.

Sunlight exposure is a key determinant of façade microbiomes. Smooth vertical surfaces exposed directly to the sun on south and west façades seem to be the most hostile environments for microbial colonization, whereas horizontal surfaces, intermittent shade and rougher surface textures support propagation of microbes as well as microbial biodiversity.

High-Rise Façade Design for Microbial Biodiversity

In the second stage of the project, we developed a façade design proposal based on the initial understanding of microbial biodiversity on building façades. At the initial stage, we conducted a one-week intense workshop in April 2021, in which three student teams (involving the project team and several additional XJTLU students) developed façade design proposals for the

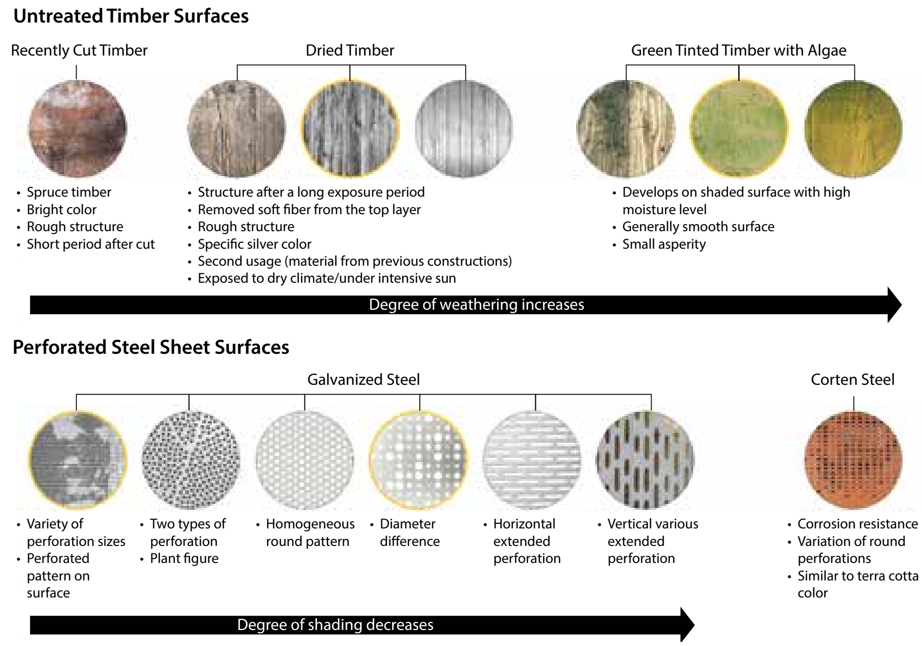

Figure 6. Microbial biodiversity in relation to substrate as a material selection starting point.

Central Building of XJTLU, the subject of the empirical stage of this study.

The final façade design proposal presented here was composed with a strong focus on translating the findings of the analytical phase of the study into a tangible design proposal. To this end, we started from the consideration of materials and their ability to create different environments for microbial colonization. A key point that emerged from the empirical study is the idea of a façade as an ecosystem composed of several layers of material, forming gradients of environmental conditions suitable for bio-colonization. Figure 6 illustrates material considerations we explored at the beginning of the proposal development. In our material selection, we aimed to identify and combine architectural façade materials according to their performance in encouraging microbial diversity, rather than pursue conventional architectural aesthetics. Based on the empirical stage of the study, we came to consider "soil" as a building material, due to its ability to sustain diverse microbial communities.

The building façade shown in Figure 7 combines several strategies to create

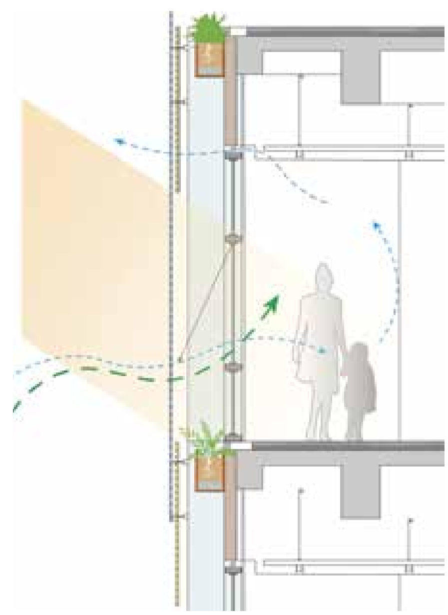

Figure 7. A façade section composed of several material layers forms a carefully constructed gradient of environmental conditions, creating a rich environment for microbial biodiversity.

microbial biodiversity at higher façade elevations (excluding fire regulations for the purpose of this study):

- The "deep façade" consists of several layers which can be configured within a 600-millimeter-deep volume. Relative distances can be adjusted according to

Figure 8. Interior view of layered façade, supporting both environmental control and microbial biodiversity.

Figure 9. Exterior view of layered façade, supporting both environmental control and microbial biodiversity. A layer of weathered bark is visible inside the perforated Corten screen.

specific environmental conditions and façade orientations.

- The exterior layer provides sun shading through perforated metal panels, as well as surfaces encouraging bio-colonization in the spandrel areas.
- The interior spaces are enclosed with a "stick-system"-type glass façade.
- On the inner façade layer, spandrel panels can also be composed of organic materials (such as cork for insulation).
- The middle façade layer features soil-filled planters made from (non-toxic) terra cotta. This offers an essential "microbial reservoir" for both the façade elements and the indoor spaces of the building.
- Natural ventilation is designed to conduct air over microbially enriched surfaces and soil before entering indoor spaces, creating healthy indoor environments.
- While bio-colonization is inherently linked to local biodiversity in the wider context around the building, we also suggest using native, minimum, maintenance plants on soil to propagate more diverse and locally adapted biodiversity, in turn supporting biodiversity at the microbial scale.

Façade Panels for Microbial Biodiversity

Extending the speculation on micro-environments, we designed façade panels capable of encouraging microbial biodiversity. The design inspiration we followed is the idea of a building clad in a material analogous to tree bark, which offers a rich environment for bio-colonization at various scales. We chose to use untreated timber for these experiments, as it encourages bio-colonization, and to be able to produce 1:1 scale panels. Figures 8 and 9 illustrate the "bark patterns" developed for the larger perforated metal sheets featured in the façade design proposal; the patterns use different geometric strategies to create varied micro-environments on each panel. From a larger pool of variations, we identified 12 patterns that could create the desired micro-shading effects.

Implications for Sustainable High-Rise Façade Design

Sustainable façade design for high-rise buildings is typically approached from the perspectives of economics, material engineering and building physics, which, while essential to producing a viable design, tend to omit the experience and concerns of flora and fauna. This contrasts with our increasing global awareness of the interconnected nature of ecosystems, and the realization that human beings require healthy, biodiverse urban ecosystems to sustain their own health and well-being in the long term. This is particularly relevant in the context of the megacities of China, where much of the population lives in high-rise buildings and is removed from direct contact with the ground. In many places, building façades form the largest part of surfaces surrounding human habitations. Yet, these surfaces are designed mostly for minimum maintenance, interesting aesthetics and sales potential.

To create healthy urban environments however, building façades, as the "new ground," should be designed not only according to current requirements, but also as devices to reintroduce urban biodiversity across all scales.

This study creates a broader understanding of how the colonization of architectural surfaces by microorganisms can be directed through design strategies. Insights gained during this project imply that a broader ecological approach beyond an anthropocentric focus is key to the future of our constructed environments. Architects may want to consider every building as an ecosystem and design it accordingly. Microbial biodiversity should be thought of systematically as a new type of building performance that has a significant impact on how buildings interact with human microbiomes, and thus with human health and well-being.

The design approach we take in this study is to create architectural façades that, in addition to their regular functions, also provide environments designed for microbial colonization. Based on our understanding of the microbial colonization patterns found on samples of diverse materials with diverse environmental exposures, we propose a layered façade design strategy, generating a "deep" façade.

The façade layers include carefully selected materials to address aspects of building performance, such as shading, while at the same time supporting microbial diversity. The sample analysis results demonstrated that conventional façade materials, engineered for ease of maintenance, discourage microbial colonization and offer only limited opportunities to support microbial biodiversity on building façades. We propose introducing small amounts of microbially diverse soil and organic materials, in combination with natural ventilation, to enhance and connect to the microbial communities found in indoor environments.

We find that this empirically-driven research approach can contribute a new perspective to conventional architectural design and integrates well with contemporary concerns for sustainability and lowering carbon emissions. This study calls attention to the role of natural ventilation in sustainable construction. In particular, in the warm and humid climates of South China, it may be useful to think about alternatives to the common emphasis on enclosing and controlling spaces for better energy management, and to create more aerial vectors for microbial exchanges between indoor and outdoor environments.

"Microbial biodiversity should be thought of systematically as a new type of building performance that has a significant impact on how buildings interact with human microbiomes, and thus with human health and well-being."

On the other hand, the emphasis on increasing microbial biodiversity invites a broader consideration of buildings as ecosystems. As microbial diversity increases with the introduction of natural substrates such as soil, plants and other living beings, we may think differently about the design opportunities inherent in building façades. This may be a cue to rethink conventional architectural aesthetics and introduce a new acceptance of co-designing buildings for living beings across all scales. ■

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