Spatial Generation, Degeneration, and Regeneration Aerotaxis Mechanisms Toward Bio-Integrated Design

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ABSTRAK: *Penelitian ini bertujuan untuk mengeksplorasi mekanisme spasial yang berkembang dalam desain bio-integratif melalui pengkajian proses alami yang kompleks dari aerotaksis. Investigasi aerotaksis menggunakan* Azospirillum brasilense *dengan mengamati perilaku dan interaksinya dalam habitatnya serta mengidentifikasi kemungkinan mekanisme spasial.* Azospirillum brasilense*, sebuah mikroorganisme yang dikenal membantu pertumbuhan tanaman dan fiksasi nitrogen, menunjukkan hubungan simbiotik dengan inangnya, yang menginspirasi pendekatan arsitektur inovatif. Dengan menelusuri pergerakannya, pola hidup, dan jejak yang ditinggalkan, terlihat adanya mekanisme khas seperti generasi, degenerasi, dan regenerasi ruang. Kerangka ini mendefinisikan ulang konsep spasial dan material arsitektur yang dianggap krusial bagi desain bio-integratif. Studi ini menunjukkan bahwa mekanisme aerotaksis menghasilkan ruang sebagai suatu kontinum dinamis, di mana material disintesis, dikonsumsi, dan diperbarui secara seimbang. Pemahaman terhadap proses biologis menawarkan kerangka alternatif dalam merancang struktur ruang yang selaras dengan sistem kompleks alam. Pendekatan semacam ini memberikan jalan untuk membangun keterikatan yang lebih dalam antara arsitektur dan proses biologis. Dengan demikian, penelitian ini menyoroti potensi mekanisme desain berbasis hayati sebagai praktik regeneratif.*

Kata kunci: *Aerotaksis, Mekanisme Spasial, Mikroorganisme, Proses Biologis, Desain Berbasis Hayati*

ABSTRACT: This study aims to explore spatial mechanism developed within bio-integrated design through exploring the complex natural processes of "aerotaxis". The investigation of aerotaxis employs the *Azospirillum brasilense* by observing its behavior and interaction within its habitat and to identify possible spatial mechanisms. *Azospirillum brasilense*, a microorganism known for aiding plant growth and nitrogen fixation, demonstrates a symbiotic relationship with its host, inspiring innovative architectural approaches. By tracing its movement, living pattern and traces show distinct mechanisms such as the generation, degeneration, and regeneration of space. This framework redefines architectural spatial and material concepts that are arguably crucial for a bio-integrated design. The study shows that the aerotaxis mechanism generates spaces as a dynamic continuum where materials are synthesized, consumed, and renewed in balance. Understanding the biological processes offers an alternative framework in designing space structures that align with nature's complex systems. Such an approach provides a pathway to foster a deeper intertwining between architecture and biological processes. As a result, the study highlights the potential of bio-based design mechanisms as a regenerative practice.

Keywords: Aerotaxis, Spatial Mechanism, Microorganism, Biological Process, Bio-based Design

1. INTRODUCTION

This study explores possibilities of more-than-human architecture that challenge the traditional view of architecture as a static and rigid form toward more responsive and adaptive architecture. Human habitats in today's modern environment are fundamentally affected by the biotechnology revolution, computing, and the long-term impacts of climate change [1]. Current architectural thinking is anthropocentric, centered on meeting human needs and interests. This anthropocentric architecture impacts ecosystems, exploiting nature as a resource for architecture. The impact of architecture has on the ecosystem is also shown on the sustainability of biodiversity and the

Earth's ecosystem [2, 3], thus demanding a different approach in designing architecture in the Anthropocene era .

Different approaches, such as the contemporary bio-integrated design, tend to shift away architecture from anthropocentric views, aiming to integrate ecological systems into architecture. Bio-integrated design becomes an approach that seeks a radical new vision in designing the future human habitat [4]. It leads to the development of designs that involve biological principles or biological devices inspired by observing how nature works. This paradigm shift represents a deeper way to work together with nature, moving beyond static principles of biomimicry to dynamic biofabrication. Drawing from biology, the study of living beings that dynamically and complexly produces billions of years of evolution [4]. Such an integration of biological systems into design radically transforms the field, expanding towards bio-integrated design.

Bio-integrated design goes further, directly engaging with living organisms in the making of materials, artifacts, and architectural systems. It holds the idea that living beings are not only sources of inspiration but active participants in material and spatial formation. In bio-integrated design, biology is not merely a reference but is physically embedded into design processes, participating in material production [5]. Collet [6] shows that, highlights biology as a language to be incorporated into design development, fostering new possibilities for material innovation. By emphasizing the dialectic between design and biological sciences [5], biointegrated design allows the collaboration with simple microorganisms, such as bacteria in yeast, as an integral part of this new craft [6].

The future of design boundaries converges within the discourse of the inanimate and animate world [6], which is possible considering the development of today's knowledge technology. Such endeavours encourage a new roadmap to connect research across disciplines, including biology [6], challenging traditional distinctions between the natural and artificial and necessitating alternative ecological design approaches. As Gazit explains [5] "The high moldability of bacterial cellulose, for instance, allows designers to shape its form by manipulating the air-medium interface during growth", illustrating how bioengineering techniques can guide the development of self-generating materials. Pasquero [1] observe that when bacteriological control became central to sanitation, it shaped modern sanitation as a new cultural and technical value system. That highlights how microbial processes can dynamically shape material formations, offering a model for adaptive and responsive architectural strategies.

Integrated with designing architecture, the study of living beings is increasingly important, as the world can be shaped by environmental factors beyond humans' control. It urges greater scientific research and architectural renewal. By exploring the aerotaxis behavior of *Azospirillum brasilense*, this study hypothesizes that such microorganism's behavior generates a particular spatial mechanism as it moves, providing a conceptual framework for bio-integrated architectural design [7, 8]. Thus, this study questions what kind of microscopic spatial mechanism can be generated and observed through aerotaxis.

Within this perspective, [4] argue that nature plays a central role, not only as a model or inspiration, but also as a medium for a layered design approach integrated biologically, materially, and socially. Bio-Integrated design becomes the basis for exploring a different design because it not only makes a shift from being centered on human interests but also exhibits sophistication as it relies on the very complex and critical systems and ways of working of nature that can be one of the offers to shape the future society.

2. INCORPORATING LIVING BEINGS AS PART OF THE DESIGN OPERATION

Based on such understanding, there should be a shift in architectural practice that incorporates a different way of operating. "The localities of architectural material exist in its singular meaning or evolve from its sourcing process" [9]. There is a diversity of nature that needs to be understood as central to architectural practice, and to achieve this, understanding ecology, native organisms, and their current states is required [10]. Starting with developing sensitivity to native species, ecological relationships, and environmental conditions, the operation must move beyond human-centered needs to foster co-dependent, adaptive, and regenerative systems.

As Thomsen and Tamke state "Living materials are manifested differently because they are more difficult to produce, manipulate, and administer." [11]. Since living materials must be cultivated or grown instead of manufactured, they differ greatly from conventional ones. Their production involves dynamic biological processes. This makes them less predictable as well as harder to control since newer approaches for design, manipulation, and maintenance remain required. De Caro [12] argues that with no architectural precedents, no idea, no relationship, and no situation can suppress or halt the urge to create space within the bounds of matter. Thus, the project can be seen as an act of introspection that absorbs natural phenomena and transforms them into creative activities.

In this sense, architecture exists as text and drawing to communicate the ideas, meaning, and experience of architecture [1], including in the physicalities of architecture itself. Just as images and text encode design intent, the life pattern of *Azospirillum brasilense* also acts as a language that embeds ecological memory and adaptive behaviour directly into the fabric of the material.

In the process of working with bio-materials, a new aesthetic is produced, introducing a level of unpredictability [5]. Growth cycles of biological actors shape their materials, their environment forms them, and their life cycles. They represent a high degree of interdependence and complex heterogeneity, including unpredictable behaviors as an outcome [11].

This variability and interdependence challenge conventional design approaches, which typically rely on uniformity and control. The act of interpretation and reproduction in architecture recognises how experiencing architecture as a whole requires individuals to capture those different dimensions and the portal relation between them [13]. "The act of reproduction creates a translation or transformation of architecture and its representation of the different needs of society" [13]. Bio-based materials, much like living organisms, respond to and are shaped by these environmental affordances, making their design inherently adaptive and context-dependent.

To truly work with bio-polymers and biomaterials, this study argues that there is a need to embrace their temporal qualities, such as decay or transformation. Rather than considering the changing characteristics as a defect that is to be eliminated, they become the essential aspects of design. As [11] explains this becomes particularly relevant for emerging design frameworks that integrate material characterization with fabrication, allowing designers to understand and respond how biological and environmental parameters actively shape material performance and lifespan over time.

Departing from such ideas, architecture needs to recognize a more diverse non-human centers of attention [14]. However, current practices often treat nature as passive, focusing on aesthetics or performance rather than engaging biological systems as active co-designers. Learning from nature can reveal various knowledge in architecture [15]. As Paramita et al suggest, "this points to a new form of interior that decentres humans as the primary focus" [16]. For instance, studying plants as concept generators for movable systems might come as a surprise because they are normally considered sessile organisms that are incapable of any motion. Plant movements usually escape our attention since they are either too slow or too small for the human eye [16]. A key gap lies in the lack of methodologies that use living organisms to shape space dynamically.

Nature is an aspect that constructs architectural space, and therefore, learning from nature is important to understand a novel architectural space [15]. Each organism defines its own space based on instinct, serving as the tools that every organism has to survive, grow, and thrive. Instinct is an innate element in every organism that drives certain behaviors. One form of instinct-driven behavior is taxi or locomotion behavior, developed by organisms as an effort to survive, influenced by various stimuli from different factors. Thus, this study addresses that gap by proposing a workflow where *Azospirillum brasilense* acts as a spatial agent, demonstrating how microbial behavior can inform adaptive, beyond the anthropocentric design.

This study employs *Azospirillum brasilense* as a model, due to its ecological significance in promoting plant growth and soil fertility, as well as its unique aerotactic behavior [4]. *Azospirillum brasilense* is a motile bacterium found in living things and widely distributed in the environment. Its behavior allows the investigation of its role in the ecosystem, particularly related to its growth and ability to fix atmospheric nitrogen to fertilize the soil. Furthermore, *Azospirillum brasilense* exhibits taxis' behavior [17], which is the capacity of motile cells to move towards a stimulus. When oxygen concentration is the stimulus, the taxi becomes aerotaxis. *Azospirillum brasilense* seeks optimum oxygen levels to survive and thrive [18].

By taking *Azospirillum brasilense*, this study serves to identify aerotaxis as a spatial mechanism, delving into a deeper understanding of biointegrated design principles. positioning humans as organisms involved in natural symbiotic relations. It shifts the paradigm towards a more inclusive ecological framework where humans and the environment coexist. Form of symbiotic architecture shifts ecological ideas, which highlight computational tools that can choreograph living processes [19] like Azos in this study, to generate adaptive spatial structure that truly "grows" in dialogue with their context.

3. METHOD OF STUDY

This study begins with an observation of the aerotaxis behavior of *Azospirillum brasilense*, to explore new potential for the search of bio-based spatial mechanisms that serve as a basis in bio-integrated design. It opens up the possibility of incorporating the aerotaxis behavior in designing architecture through a micro approach [20, 21]. In this study, a micro observation was conducted to examine the behavior of *Azospirillum brasilense* and its spatial interaction within its environment, particularly focusing on the conditions that influence its relationship with other organisms [22, 23].

The observations were conducted using a digital microscope with recording capability. The bacterial samples of *Azospirillum brasilense* used in this study were sourced through an online purchase from the e-commerce platform that offers a range of agricultural and microbiological products. The bacterial samples were marketed as plant growth-promoting bacteria commonly used in biofertilizers. While unconventional for academic sourcing, this method reflects a more accessible and practical approach to obtaining live microbial cultures for independent research.

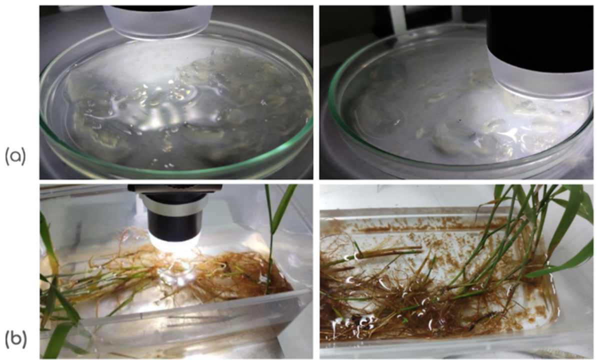

Figure 1. Observation of *Azospirillum brasilense* Under Controlled and Mixed Conditions, Forming The Basis For Spatial Interpretation
Source: Authors (2023)

The methodology compares two microscopic observations under two distinct conditions, one after another. The first observation is Azospirillum in isolation within stained culture cups without the presence of other organisms or plant matter. The second observation, conducted sequentially, is when the bacteria coexist with other organisms in a mixed environment. Row (a) in Figure 1 shows how Azospirillum brasiliense was placed in a preparation and isolated to avoid confusion with other organisms during observation to identify and understand its behaviour and characteristics (row a). Meanwhile, row (b) shows how the Azospirillum brasiliense was released into an environment for further observation for a better understanding of its behaviour in the environment and the interrelation with the host organism.

After the micro observation was conducted, the next phase was to compile and organize all data obtained from the observation into a catalog for more systematic categorization (Figure 2). In total, 80 visual data points in 720p video format were converted into a series of scene images for analysis. To ensure reliability, the observations were conducted sequentially under both controlled and mixed conditions, allowing direct comparison across different environments. From these recordings, behavioral patterns were traced and categorized systematically to identify recurring mechanisms, reducing the possibility of random interpretation. In addition, findings were discussed with a microbiology expert to validate the interpretations, thereby strengthening the credibility of the results and minimizing observational bias.

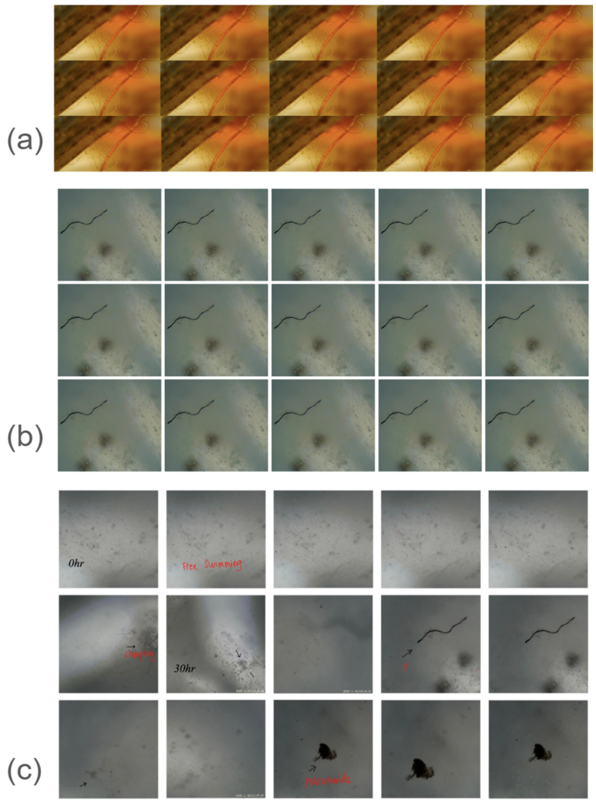

Figure 2. Visual Documentation of Bacterial Behaviour From The First Observation (a), The Second (b), And Visual Annotation of Polysaccharides Generated From The Bacteria (c)
Source: Authors (2023)

While the development of new materials has traditionally been led by engineers and material scientists, designers are now beginning to take a more active role. The collaboration is not only shaping but also cultivating and co-creating new living materials [6]. Thus, the investigation was complemented through a dialog with a microbiology expert to deepen the understanding of *Azospirillum brasilense's* behavior. This dialog helped bridge empirical observations with scientific insight, extending the idea of bio-integrated design.

4. RESULT AND DISCUSSION

4.1. Identifying the mechanism within the aerotaxis of *Azospirillum brasilense*

Based on the above observation, the aerotaxis behaviours performed by the organism *Azospirillum brasilense* in various environmental situations can be identified as material and spatial mechanisms of a symbiotic relationship. In controlled conditions, *Azospirillum brasilense* was placed in a stained cup and not mixed with other organisms. As the observations were conducted over several days, black blobs were spotted under the microscope just a few days after the start. Clarified by the biologist, the black clumps would be polysaccharides, a substance produced through a self-generative process by the organism as a defense mechanism to ensure the survival of the colony. Bacterial respiration in an oxygen-permeable sealed glass capillary at one end created an oxygen gradient in our observations, resulting in a band of bacteria moving towards the oxygen source. The process is known as a band formation [18].

Here, polysaccharides have a role in nature's complex system, and their ability to be naturally produced by organisms such as Azospirillum. As a result of the bacterial metabolic process, polysaccharides function not only as a source of energy and protection, but also as a defence mechanism against environmental stress. The bacteria alter the polysaccharides as an adaptation to environmental conditions, creating a more responsive and regenerative building system. The intertwining process between the bacteria and the polysaccharides shows how the organisms utilise the surrounding environment to survive and thrive. It can be seen that such a biological process allows material to constantly evolve and change, rather than remain static.

On the other hand, a different pattern between organisms can be identified when the bacteria are mixed with the grass plants. The observations focused on the root area by paying attention to the behaviour of the *Azospirillum brasilense* that inhabited the roots of the plant as its host. The relationship between the *Azospirillum brasilense* and the grass involves the flavonoid. The flavonoids are significant in the symbiotic relationship because they act as a chemical cue, guiding the bacteria to the plant's roots. This interaction is crucial for the establishment of the symbiotic relationship, as it encourages the colonization of the root by *Azospirillum brasilense*. Upon reaching the root, *Azospirillum brasilense* benefits from the plant's rhizosphere, where the bacteria can form a stable association with the plant through the 'communication bridges'. They promote growth by fixing nitrogen and enhancing nutrient uptake. This generative phase supports the bacteria's survival and growth and highlights a biological system's dynamic and interconnected processes.

In the same process, bacteria not only respond to the presence of flavonoids as aerotaxis but also consume the compounds, which in some cases leads to reduced flavonoid concentrations around the root surface. The process of consuming flavonoids can be interpreted as part of degeneration. Degeneration here is understood not simply as destruction, but rather as a change in microenvironmental conditions. The loss of flavonoids alters interaction patterns, weakening the chemical signals that originally cemented the symbiosis. Spatially, this can be understood as the elimination or reduction of the communication bridges between roots and bacteria, which in turn provokes a transformation of the microenvironmental structure. Thus, flavonoid consumption by *Azospirillum brasilense* is a natural mechanism of degeneration that is important for understanding the dynamics of more complex relationships between organisms and their environment.

What then happens is that as the *Azospirillum brasilense* consumes flavonoids in the surface area of the root, there is a reduction in the concentration of these compounds. Interestingly, the root responds to this consumption by reproducing flavonoids in the areas that were previously consumed. This mechanism can be interpreted as a regeneration process. Regeneration here is understood as the ability of the living environment, in this case, the root, to renew its microspatial conditions after undergoing changes or degradation. The reproduction of flavonoids is not just a recovery, but also an active effort by the root to maintain, strengthen, and manage the symbiotic relationship with the bacteria. Such understanding of the aerotaxis behavior of *Azospirillum brasilense*, either in homogeneous or in mixed conditions with other organisms, offers valuable insights into how living organisms actively shape, transform, and renew their environments. *Azospirillum brasilense* does not function in isolation; it interacts with plants and other microorganisms, facilitating nitrogen fixation and influencing soil health. Rather than functioning in isolation, *Azospirillum brasilense* engages in continuous interactions with plants and other microorganisms, contributing significantly to ecological processes such as nitrogen fixation and soil health maintenance.

4.2. Generation, degeneration, and regeneration as spatial mechanisms

Based on the elaboration above, three patterns of behaviors are developed during the symbiotic relationship between the *Azospirillum brasilense* and the grass root can be identified: growth or generation, reduction or degeneration, and reproduction or regeneration (Figure 3). These relationships can also be seen as the mechanism of spatial generation, degeneration, and regeneration, which will be further discussed as a crucial spatial mechanism in developing bio-integrated design.

Generation refers to how *Azospirillum brasilense* contributes to creating or modifying spaces through its activities, such as aiding plant growth and nitrogen fixation. In the context of bio-integrated design, this spatial mechanism can be understood as the process of creating new spaces or conditions through the biological activities of organisms. In this study, *Azospirillum brasilense* demonstrated a generation mechanism through the release of chemical signals such as flavonoids from plant roots, which triggered colonisation and the formation of symbiotic relationships. This mechanism can be translated into a principle that focuses on creating initial conditions that stimulate interaction, growth, and organic formation of space. This implies that designing space no longer relies on forms imposed from the outside, but rather facilitates the occurrence of structure and function through the internal dynamics of the system itself.

Degeneration, refers to the bacterium's role in consuming or breaking down existing conditions, rather than restoring them. In biological terms, degeneration is observed when *Azospirillum brasilense* consumes flavonoids, leading to the loss of chemical signals on the root surface and disrupting pre-established interaction patterns. Translated into architectural terms, degeneration of space highlights the dismantling, decay, or fading of existing spatial structures. Rather than being a restorative act, degeneration enables natural transformation by clearing, weakening, or removing certain elements, thereby creating the conditions for subsequent regeneration.

Regeneration involves how the bacterium interacts with its environment in ways that lead to the breakdown or alteration of existing spatial structures or conditions. The regeneration mechanism in bio-integrated design refers to the process of recovery, renewal, and adaptation of space after undergoing a degeneration phase. Based on observations of *Azospirillum brasilense*, regeneration occurs when the roots respond to the consumption of flavonoids by the bacteria by reproducing the compounds, renewing chemical signals, and strengthening symbiotic relationships. The regeneration of space can be translated into the principle of creating systems capable of renewing themselves without reliance on major external interventions.

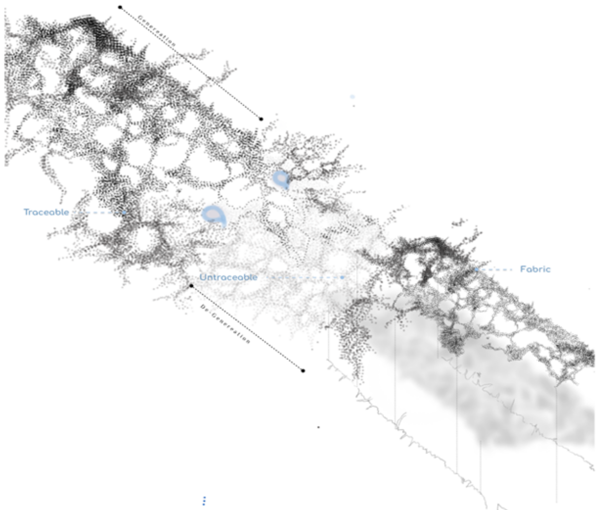

Figure 3. Spatial Mechanisms of Generation, Degeneration, and Regeneration Derived From Aerotaxis Behavior.
Source: Authors (2023)

4.3. The Nutrition, the Hunt, and the Nest as Spatial Models

Employing these spatial mechanisms in design practice requires translating nature's complex systems into operations that can be understood, processed, and applied in the context of architecture and the built environment. Thus, to further elaborate such design principles, this study proposes a conceptual model that reflects the spatial mechanisms of aerotaxis. The conceptual model based on *Azospirillum brasilense's* aerotaxis represents the biological and spatial integration, consisting of the Nutrition, the Hunt, and the Nest. They portray the spatial ideas of each mechanism for translating microbial behaviour into architectural design. Each mechanism is translated into a spatial model that embraces the principles.

The Nutrition depicts the first mechanism of *Azospirillum brasilense's* aerotaxis, highlighting the creation or transformation of space. It is particularly evident in the way it facilitates plant growth through nitrogen fixation. As *Azospirillum brasilense* indirectly participates in the development of the root structure and the soil environment, it involves the production of polysaccharides. The Nutrition highlights how generation takes place (Figure 4). In the generation, plant roots act as an active agent that initiates interaction by releasing flavonoids as organic signaling compounds into the surrounding environment. Triggering the *Azospirillum brasilense* movement toward the root zone facilitates the formation of a symbiotic relationship, leading to spatial generation through colonization, nutrient exchange, and microenvironmental transformations around the root surface. This flavonoid release from roots acts as a spatial and biological generator, setting the conditions for new ecological material formations.

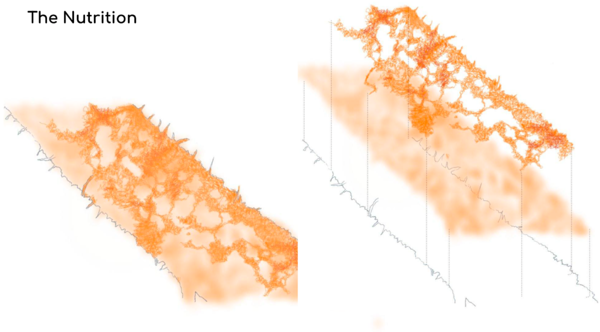

Figure 4. "The Nutrition" as a Model of Spatial Generation Through Microbial–Plant Symbiosis
Source: Authors (2023)

The employment of spatial generation encourages architecture that can shape itself as the components within it grow, interact, and change. Thus, Nutrition becomes a living and evolving open system, rather than a static entity. This principle introduces a more responsive approach to design, allowing spaces to take shape as a result of the evolving relationships between people, materials, and other living organisms.

The Hunt shows how the bacteria deconstruct or break down existing material in their spatial conditions. It highlights a necessary mechanism in ecological cycles through its interactions with other microbes. It becomes a biological pathway. The consumption of resources or the breakdown of certain organic matter contributes to the continuous transformation of its habitat, a cyclical process that enables spatial renewal (Figure 5).

Instead of avoiding degradation, this spatial model considers a necessary phase to create the dynamics of adaptation in biological processes. The Hunt shows how architecture allows for wear and tear, fading, or change, which then opens up opportunities for new conditions to be created. Degeneration mechanism encourages the creation of a built environment that not only accepts change but also uses it as a tool for continuous spatial evolution. As such, degeneration is not seen as a design failure, but rather as an integral part of the life cycle of space and materials.

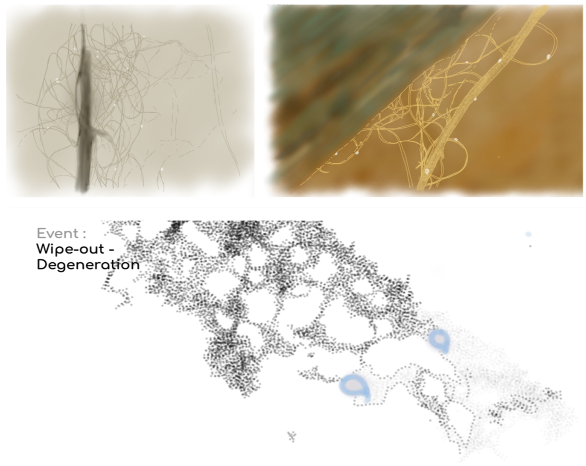

Figure 5. "The Hunt" as a Model of Spatial Degeneration Through Consumption and Transformation
Source: Authors (2023)

The Nest is conceptualized based on *Azospirillum brasilense's* ability to restore, adapt, and reconstruct space following degeneration or disruption. This ability was particularly visible in the symbiotic relationship observed in the root's plant environment. When *Azospirillum brasilense* colonizes the surface of the root, it becomes an assemblage (Figure 6). It not only occupies space but also activates the Hunt, the biological pathway, that enhances the resilience and health of the plant system. Through this interaction, the Nest helps rebuild ecological balance and ensures the continuity of space as a living environment.

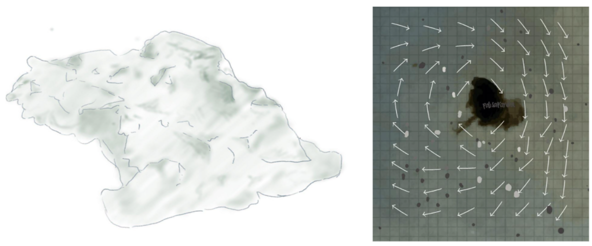

Figure 6. "The Nest" as a Model of Spatial Regeneration Through Ecological Rebuilding
Source: Authors (2023)

The Nest, as a regenerative model, encourages the creation of materiality and spaces that are responsive to changing environmental conditions, able to adapt, repair, and organically reshape their structures. It introduces a design principle that is not only oriented towards initial construction, but also towards long-term cycles of renewal. By understanding regeneration as a natural part of living systems, architecture becomes more sustainable, resilient, and harmonious with the rhythms of ecological change. Architecture is no longer seen as a final product, but rather as a system that continues to evolve with its environment and inhabitants.

5. CONCLUSION

This study discusses aerotaxis as a basis for developing a spatial mechanism for a conceptual model toward a bio-integrated design. This study illustrates a design methodology developed based on a complex biological process observed through the *Azospirillum brasilense* and its aerotaxis behavior. It demonstrates how the interactions between the organism and its surroundings can be understood as mechanisms of generation, degeneration, and regeneration of space, providing a basis for the conceptual model–the Nutrition, the Hunt, and the Nest.

Based on the discussion above, this study can demonstrate the importance of understanding nature as a non-linear, complex, and unpredictable system, allowing architecture to become adaptive, dynamic, and interdependent. Learning from the aerotaxis mechanism, a continuum of generation, degeneration, and regeneration mechanisms organically shapes and transforms spaces. By understanding these mechanisms, the study seeks to translate them into principles employed in the bio-integrated design. By documenting and categorizing the aerotaxis behaviours, this study shows how microbial life provides principles through its interactions with the environment and its self-organizing behaviour materially and spatially. The dynamic character of ecological systems is reflected in such mechanisms, where space is continuously created, altered, and renewed based on the biological processes. Such processes generate an alternative framework for designing space structures that align with nature's complex systems.

With a focus on the spatial mechanisms, this study demonstrates that the relational behavior between organisms and their environment, for instance, the bacterium's reaction to plant roots or compounds secreted by the roots, like flavonoids, can give rise to spatial programming. Biological elements are produced, consumed, and renewed through these mechanisms, which act as design logic to create spatial systems that are adaptive and dynamic. This causes the architectural paradigm to change from fixed forms to biologically shaped processes of spatial becoming. Expanding on Collet's assertion, which highlights the significance of developing bio-integrative and adaptive architecture, this study also rethinks how architecture in the Anthropocene becomes a living system that interacts with and adapts to its natural surroundings. Such an approach creates a pathway to foster a deeper intertwining between architecture and biological processes.

It can also be demonstrated that the bio-based design mechanisms have the potential for a bio-integrated design as a regenerative practice. The complex behavior of microorganisms raises further questions on innovative design method, procedures and deeper interdisciplinary collaboration, as a way of developing future bio-integrated design. It is unavoidable for architecture to work on multiple scales to capture nature's dynamic, including the microorganism, creating an alternative materiality and spatiality toward a bio-integrated design. Thus, prototype-based experiments and the creation of real-time mapping tools to visualize biological interactions could be used to investigate this framework further. Future architecture should not only be built to last, but also to change over time.

6. ACKNOWLEDGMENT

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