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Bioreceptive Ceramic Surfaces: Material Experimentations for Responsible Research and Design Innovation in Circular Economy Transition and "Ecological Augmentation"

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Abstract: The world demands suitable design solutions to transition toward a sustainable production system. The concept of sustainability evolves with technology's ability to understand and replicate nature's logic. There is a growing need to move beyond punctual solutions towards more intricate and multi-stakeholder considerations, including preemptive assessments of impacts. This article discusses the outcomes of cross-disciplinary material experimentation at Saperi&Co Center, Sapienza University of Rome. This research focuses on enhancing ceramic surfaces through circular economy practices, making them receptive to microorganism colonization—known as bioreceptivity. Through an iterative and repetitive approach, inspired by Research Through Design and material experimentation, several experiments were carried out to study how the innovative use of organic waste in clay-based mixtures can promote bioreceptivity and the design of green surfaces for urban regeneration. The results advance our knowledge on the multiple parameters the designer must consider to transform inert surfaces such as ceramics into "ecological augmentation" devices. The article also aims to raise awareness of bioreceptivity as a practice to educate communities about a symbiotic relationship with nature, promote local economic development and circular production, and prompt reflection on cultural aspects arising from contemporary scientific and technological advancements in line with Responsible Research and Innovation (RRI) principles.

Keywords: bioreceptivity; ceramic; circular economy (CE); organic waste; porosity; Responsible Research and Innovation (RRI); ecological augmentation

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1. Introduction

"Good design can be an agent of positive and sustainable change. By developing thoughtful manufacturing processes which reduce waste or use it as a new material, [. . .] designers can bring empathy and respect for organisms and ecosystems into their practices [. . .] emphasizing our responsibility to the well-being of future generations". This is the access panel to the exhibition "Life Cycles: The Materials of Contemporary Design", currently taking place at the Museum of Modern Art in New York, curated by Paola Antonelli (MOMA, 2 September 2023–7 July 2024). The exhibition explores the regenerative power of design and its role in ecological transition, experimenting with new materials and ways to use our world's resources in a balanced manner.

In the same way, the study described here started from the assumption that traditional materials and waste materials can contribute to a rethinking in design, fueling a sustainable creative process that embraces the circular economy, a model based on the repeated return of materials, components, and products back to the production process [1,2]. The concept of sustainability has indeed evolved over the years, and thanks to continuous technological progress, numerous attempts are being made to draw inspiration from and replicate the logic of nature, aspiring to surpass discrete circular solutions with a low energy impact towards more systemic, multi-stakeholder, and preventive solutions [3].

New materials and approaches to sustainability also require the development of innovative aesthetics that can educate the community about the values of environmental responsibility and symbiotic collaboration with nature. An example is the biocolonization of urban surfaces by living organisms such as algae, fungi, and moss. While previously considered a symptom of neglect or degradation, in recent years, it has been reevaluated as a phenomenon with high aesthetic, functional, and sustainable potential for urban regeneration (Figure 1). The increasing use of these forms of "greenery" reflects a shared desire to transform the image of dense, heavily urbanized, and monotonously grey cities, reshaping the semantic–communicative framework of the city and giving it a recognizable identity that emphasizes ecological and environmental concerns [4]. Therefore, not limiting itself to the aesthetic dimension, this approach attributes an overall value to the urban landscape, shaping the continuity between the anthropic and natural environments [5,6].

Figure 1. Travertine sidewalk threshold with microvegetation, Rome.

Starting from these premises, this contribution presents material experimentation that was carried out to "enhance" a potentially inert material into a bioreceptive one—predisposed to biocolonization—through circular practices. Considering the process of "ecological growth", an attempt has been made to render clay-based materials suitable for hosting and nurturing living matter to create "green" surfaces that contribute to new forms of urban regeneration and aesthetic languages that catalyze symbiotic interactions between city dwellers and nature. Specifically, the project utilizes organic waste to render ceramic surfaces bioreceptive. Mixed with clay, the organic waste disappears following the firing process, leaving voids, porosities, and heterogeneities that, managed through design, allow for "choreographing" biocolonization patterns for desired aesthetic and functional purposes. The transformative potential of the circular design approach lies not simply in using waste materials as fillers but in valorizing them as a design element to enhance the performance of the surrounding material environment. Therefore, the research presented herein explores how hierarchical material, structural, and geometric complexities can be managed based on numerous factors, such as the type of waste, the quantity used, the application technique, the material process, and the cultivation of living matter. It evaluates how variations in these factors can promote surface biocolonization, enabling designers to control levels of bioreceptivity and achieve desired growth patterns.

The project relates to the urban area of Rome and the banks of the Tiber River, influencing the choice of aesthetics, production techniques, and organic waste. Among the latter, cardboard pulp and coffee grounds were chosen because they can provide various types of clay-based materials with different morphologies and pore sizes, thus leading to different and comparable degrees of bioreceptivity. Additionally, the production of paper, cardboard, and coffee grounds is significant, and many of these materials end up in landfills. In Italy, approximately 3.6 million tons of waste paper and cardboard are produced annually, of which 700,000 tons are sent to landfills [7]. At the same time, it is estimated that about 500,000 tons of coffee grounds are produced each year, with the majority (360,000 tons) ending up in landfills [8]. Through the selection of these waste materials, the project also aims to promote local circular production, as these are significant waste materials in the Lazio Region (surrounding Rome) able to foster Industrial Symbiosis [9], and the development of distributed micro-economies for the growth of startups and Small- and Medium-sized Enterprises (SMEs). In this territory, the number of paper mills is high, with these mills having important impacts at a European level, and there is also historical–cultural heritage, as well as know-how that has been developed since the 17th century [10]. This region also produces a large amount of waste material: Lazio produces 79,975 tons of industrial waste annually from wood and paper processing [11], in addition to 17,309 tons of waste paper and cardboard from urban separate collection [12]. Furthermore, Lazio is among the top three Italian regions for espresso coffee consumption [13], and Rome, along with Palermo, is the Italian city where espresso coffee from bars is consumed the most [14], resulting in a large quantity of waste coffee grounds that could potentially be utilized.

The project's outcome is a set of guidelines for creating bioreceptive ceramics using design principles and organic waste. This research represents progress in understanding porous ceramics and bioreceptive design, which are typically focused on using concrete as the primary construction material. While concrete is widely used, especially for structural elements, ceramics offer an attractive material alternative, particularly for surface applications such as facades and cladding. The experiments align with the broader goal of regenerating urban spaces and existing structures through lightweight, modular, and easily installable coatings.

The chosen approach ultimately aligns with the principles of Responsible Research and Innovation (RRI) [15], supporting the need to guide current technological possibilities towards a truly regenerative perspective and promoting research towards shared future scenarios involving multiple scientific fields and various innovation stakeholders [16].

1.1. Responsible Research and Innovation (RRI) and Material Experimentation

The research described below is part of RRIStart, a EU funded project initiated in 2021 within the RRI framework [17]. This project is a collaborative effort that combines the ethical principles of RRI [18,19] with the practical approaches of startups engaged in high-tech and innovation sectors where the issue of responsibility takes on special significance as new actors and markets address it, with the impacts being unclear [20]. RRIStart refers to a "translational approach"—from the laboratory to the market—that starts from experimental practices to address complex social issues and is based on the Quadruple Helix approach [21], meaning that innovation occurs as a result of the behaviors and interactions of different stakeholders aimed to pursue specific values typical of the four main sectors, or "helices", of society: Industry, Politics, Research, and Civil Society. Within this framework, innovation is not solely perceived as an intellectual effort to find new solutions to problems; rather, it is a social effort in which society and science change together and mutually influence each other. The concept of Responsible Research and Innovation (RRI) is, therefore, a way of "taking care of the future through the collective management of science and innovation in the present" [15]. So, RRI is a valuable testing ground for designers, prompting research aimed at rethinking materials, techniques, and approaches.

An approach to responsible innovation management inspired the experimentation outlined in this study. The goal is to promote the creation of new interdisciplinary, nature-based, bio-oriented, and socially conscious economic avenues. In particular, an attempt was made to apply specific points from the RRI toolkit [22] to overcome a "technical challenge" through a multi-stakeholder approach. This led to selecting a theoretical and practical method, opening the experimentation process to a diverse team of researchers with a wide range of interests and expertise (design, urban planning, accessibility). The research community was further enriched by including a designer who specialized in processing clay-based materials, providing the group with the necessary knowledge of the material being explored. This also served as a bridge between research and industry, demonstrating the potential of design in envisioning and catalyzing new, highly innovative realities that can be realized within an economically competitive and risky context, such as that of start-ups. In particular, the attention paid to small entities such as SMEs, artisanal businesses, and artistic laboratories, which are the leading players in the Italian entrepreneurial context, is extended from the realization that more systemic circular economy practices, referring to the establishment of widespread micro-economies through Industrial Symbiosis (IS) practices [23], knowledge exchange, and circulation of new resources, can effectively support entrepreneurial initiatives grounded in responsibility and common benefit (social, economic, and environmental).

1.2. Bioreceptive Surfaces

Nature's system is inherently regenerative, with each element naturally fostering and sustaining new life. This is critical in cyclical processes like biodegradation, where catalyst microorganisms transform materials, extracting essential nutrients for new life to thrive. Additionally, this regenerative capability is vital for the maintenance of ecosystems and mutual benefit among the individuals within them, achieved through symbiotic relationships, interaction, and permeability among parts, ultimately leading to the emergence of new functions and conditions.

Take, for example, bioreceptive surfaces, which are susceptible to colonization by one or more groups of microorganisms without necessarily undergoing biodeterioration [24]. In nature, a prime example is tree bark, which, due to its structure and materiality, acts as a host for propagating microorganisms (e.g., cyanobacteria), cryptogams (such as ferns, mosses, lichens, algae, and fungi), or other more complex organisms. It is also a permeable membrane mediating between internal and external conditions [25]. The concept of bioreceptivity has gained prominence in recent decades in the fields of construction, material sciences, and ecology. It has sparked numerous studies that, surpassing the negative connotation of biological colonization, seek to transform surfaces in the built environment into "ecological augmentation" devices without additional external technical support [24]. Bioreceptive surfaces can offer numerous advantages. The green layer can protect exposed material from weathering and provide thermal and acoustic insulation to architectural elements [26]. Photosynthetic microorganisms and small non-vascular plants growing on these surfaces can absorb up to 3.9 Pg of carbon annually on a global scale (equivalent to about 7% of the net primary production by terrestrial vegetation) and 49 Tg of nitrogen [27]. They can trap dust and other impurities, purifying our air [28]. The presence and movement of water through the vegetative layer contribute to cooling the surrounding air through evapotranspiration [29], addressing the issue of urban heat islands and reducing the cooling load on buildings. Moreover, as bioreceptive facades result from the material properties of the main building fabric, they are autonomous and self-sufficient systems that do not require additional costs (economic and energy-related) or maintenance structures, unlike typical green wall systems.

Bioreceptivity, therefore, indicates the likelihood of a material being biocolonized and is becoming an increasingly fundamental phenomenon in sustainable design and material experimentation. The bioreceptivity of a surface depends on various variables related to the environment, organism properties, and substrate material properties [30], defining a working area that challenges design to explore the relationship between these elements to develop strategies that enhance or inhibit the growth of living organisms. As it involves biological growth, bioreceptivity is also dynamic, as the material and environmental conditions can change over time. Guillitte defines four types of bioreceptivity that can occur in a rocky material (Figure 2) [24]:

1. **Primary or intrinsic bioreceptivity:** Indicates the initial potential of a material to be colonized, and its properties remain identical even after the appearance of the first organisms.
2. **Secondary bioreceptivity:** The potential for colonization changes (increases or decreases) due to variations in material properties caused by the action of the colonizing organisms or environmental factors.
3. **Tertiary bioreceptivity:** Material property variations are due to human action, influencing the material's primary or secondary bioreceptivity.
4. **Extrinsic bioreceptivity:** The potential for surface colonization is not directly and exclusively related to the material properties but is influenced by a layer of materials (soil, dust, organic particles) that can promote or inhibit biological growth. This occurs, for example, in the colonization of surfaces by heterotrophs (such as mosses and lichens) following and depending on the growth of phototrophic organisms or "pioneers" like algae and cyanobacteria [31,32]. The latter changes the chemical environment, creating new conditions for other species to enter, forming mutualistic reactions with the previous ones or replacing them [33].

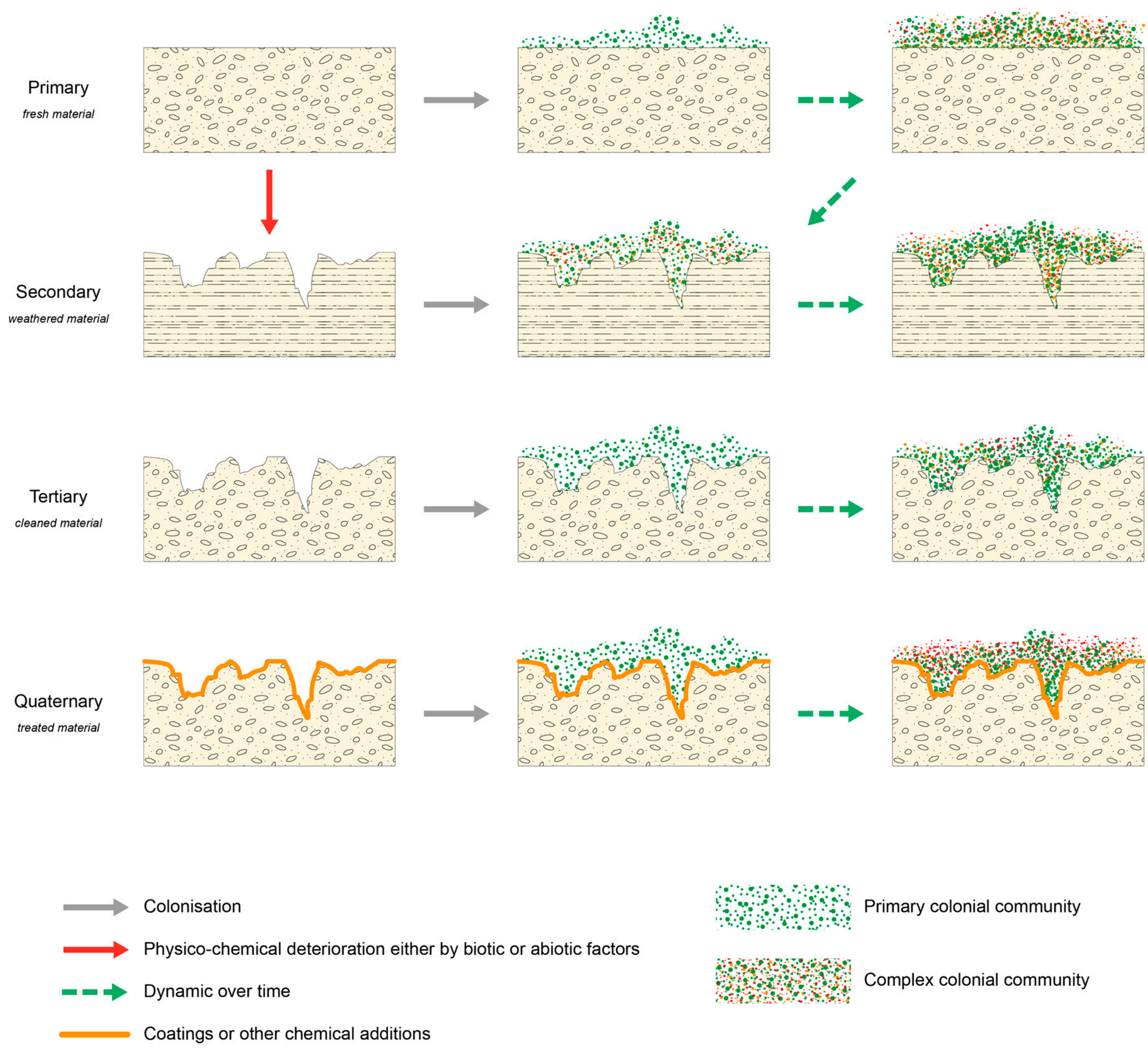

Figure 2. Visualization of the four bioreceptivity categories. The arrows indicate the changes over time. Scheme inspired by [30].

In both nature and the built environment, these stages of bioreceptivity can occur and coexist, leading to the symbiotic growth of various organisms starting from a "biofilm". A biofilm is a complex aggregation of microorganisms characterized by the secretion of an extracellular polymeric matrix that protects and binds cells to a surface [34,35]. However, although the involved species (especially "pioneer" organisms) are highly stress-tolerant [36], they still have requirements that must be met in the substrate they inhabit for survival and prosperity. Observational research has identified some fundamental characteristics that a material must possess to be potentially bioreceptive. For simplicity, these characteristics can be categorized into intrinsic and extrinsic factors. Regarding intrinsic factors strictly related to the material and its composition, the fundamental physical properties identified include surface roughness and high porosity. Chemical properties include surface pH, which must be neutral or below 10 [25], and mineral composition, including nutrients and substances that stimulate cell growth, such as phosphorus [37]. Surface roughness helps create a microclimate, trapping moisture from the external environment and shading cells [38,39]. Conversely, porosity is crucial for spore entrapment and maintaining a high capillary water content, providing the necessary moisture for microbial survival [40,41]. Concerning extrinsic factors, despite often being overlooked, architectural and structural characteristics of supports and contextual factors are crucial and significant for choosing a suitable material and living species in a given environment [30,42]. "Architectural" characteristics refer to the morphology and geometry (surface and structural) given to the support, contributing to either supporting or inhibiting the bioreceptivity of a material surface [43]. Environmental factors, on the other hand, relate to meteorological conditions (which depend on monthly average temperature and relative humidity), air quality (which depends on the presence of substances such as NOx, SO_2, CO, and O_3), and the presence of organisms in the environment (e.g., bacteria) that can either promote or hinder the growth of other species [42].

In recent years, architects and designers have shown a growing interest in understanding and managing the factors related to bioreceptivity. Engaged in multidisciplinary teams, their overarching goal is to educate the community about a new aesthetic that does not associate the biocolonization of building surfaces with signs of deterioration or disorder [44] but rather as an element with multiple benefits to emphasize and promote a sustainably performative and biologically integrated architecture. Noteworthy is the research conducted for over a decade by professors Cruz and Beckett at the Bartlett School of Architecture (UK), encapsulated in the comprehensive term "Bioreceptive Design" [45]. They experimented with biocolonization in architecture, specifically exploring the possibility of controlling the growth patterns of living organisms on construction materials through design. Their projects focus on the engineering design of bioreceptive supports in different materials (mainly concrete and its aggregates but also hydrogels based on Curran, sodium alginate, and cellulose) and for different biological species, such as algae, mosses, and fungi [45–48].

Another area of research shifts its focus to the possibility of making fabrics bioreceptive for use in various fields, from fashion [49] to architecture. For example, Blaisse et al. experimented with lightweight, mobile, and translucent textile systems for architecture that allow for the growth of microorganisms on their surface [50]. They explored how different natural fibers (cotton, linen, hemp) and various processing techniques (weaving, knitting, felting) for creating various textures and patterns influence the growth and distribution of organisms.

Clay-based materials are at the core of experiments conducted by the startup Urban Reef [51], whose mission is to create open-ended habitats that encourage the growth of diverse living species to regenerate urban spaces. They focus on a dual approach: making the surface of fired clay usable for biocolonization through the application of biofilms in a hydrogel containing spores of living material and making raw clay bioreceptive by mixing it with spores, organic coffee waste, paper, sawdust, and river sediments [52]. Similarly, the IOUS studio [53], composed of architects and designers Sol Sanchez Cimarelli and Agustin Ros, creates "bioreceptive ceramic tiles" using a similar approach.

In the same way, this research focuses on clay-based mixtures and implementing their bioreceptivity through organic waste. However, the approach is different: waste is not merely a filler or nutrient but a design element used to manage micro-, meso-, and macro-porosity so that it can favor or inhibit biocolonization on urban surfaces for various aesthetic and performative purposes. This broader interpretation aims to give a more profound meaning to circular economy practices and the concept of waste as a new resource. It emphasizes the regenerative potential of ecological intelligence and functional adaptation to contexts and situations through design, showcasing it to the community through the resulting aesthetics [54].

2. Materials and Methods

The project followed a mixed methodology divided into two main phases. The first phase adopted a top-down approach by analyzing scientific literature on bioreceptivity and design, specifically reviewing case studies, methodologies, biomimetic approaches, and circular economy principles. This represented the basis for guiding subsequent experiments Section 2.1. The analysis also covered the study of materials, particularly clay-based mixtures Section 2.1.1; potential waste materials helpful in creating porosity in the mixture Section 2.1.2; biological matter, with a focus on cyanobacteria; and the environmental conditions necessary for its proliferation Section 2.1.3.

The second phase followed a bottom-up approach that involved applying the acquired knowledge, especially looking at the opportunity to experiment with the composition of bioreceptive clay-based material combinations at three identified porosity levels (micro, meso, and macro) Section 2.2. To explore various design opportunities, the experimental phase concentrated on creating slabs characterized by various compositions, porosities, and surface geometries. The aim was to verify the possibility of achieving a controlled bioreceptivity by design, predicting the growth trends of living matter based on the morphological and material configuration of the designed support surface. This approach fits within the broader perspective of Research Through Design (RtD) [55], an approach to scientific investigation that employs the tools and insights of design practice to understand complex and future-oriented issues better [56,57]. Based on these premises, the process followed an iterative (repetition of phases) and recursive (repetition of the process based on previous verification) methodological framework for the entire process. This framework can be summarized as follows: Hypothesis–Fabrication–Growth–Validation–Thesis (Figure 3).

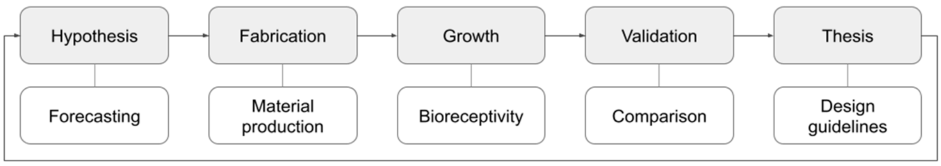

Figure 3. Methodological framework adopted for the research. It is based on RtD principles, and it refers to a reflective practice characterized by iterative and recursive phases.

2.1. Design Process Setup

Research Through Design (RtD) methodologies are also relevant for interdisciplinary research spanning scientific and design disciplines, such as bioreceptivity studies. Through a laboratory protocol and reflective practice, it is possible to define modes of action, variables to consider, and a series of repeatable and reproducible steps to validate results and propose new guidelines for their scientific refinement. In particular, the following research focuses on the possibility of growing living cells on supports with specific, defined, and even complex properties and geometries. A solution to this challenge can be derived from biofabrication, specifically the scaffold concept. “Scaffold design” aims to develop design and production strategies for creating “scaffolds” capable of hosting and growing living cells to expedite and perfect their production processes and achieve specific, detailed, and modulated properties consistently across all scales [58]. It originates from biofabrication, a multidisciplinary field whose goal is “the production of complex biological products, living and non-living, from raw materials such as cells, molecules, extracellular matrices, and biomaterials” [59]. Initially referring to tissue engineering and regenerative medicine to develop biological substitutes to restore, maintain, or improve the functions of biological tissues or entire organs [60], biofabrication today encompasses a broader set of methodologies and technologies applicable in design to implement a material-based biological paradigm, applying the logics of nature to material and production scales for more sustainable processes and products with complex, customized, and emergent biological qualities [61].

Building on these premises, the research is based on material experimentation and seeks to apply some principles of "scaffold design", such as hierarchical structural properties and smart-surface characteristics [62], to make ceramic surfaces bioreceptive for application in architecture and construction. In particular, the concept of porosity is referenced in the broadest sense and across multiple scales, while at a strictly physical and technological level, porosity indicates the ratio of open pore volume to material volume, determining its permeability to fluids and air [41]. In our case, porosity is generally understood as the presence of voids, interstices, and irregularities relative to the total mass of the body, determining the material's overall permeability to biological growth. These discontinuities are managed at three-dimensional levels (micro, meso, and macro) by varying the type and quantity of mixed or impressed waste material on ceramic surfaces. The three levels follow the hologrammatic principle, meaning they employ strategies that interact with each other and contribute equally to the final rendition of a complex system [63]. They are specified as follows:

- *Micro-porosity:* Micro-porosity refers to the intrinsic properties of the material, particularly its physical characteristics of surface roughness and porosity. The combination of these factors can contribute to the adhesion of cells to the material support, create an optimal microclimate for their growth, and achieve the proper levels of water permeability and nutrients necessary for their development, promoting what is termed as the *primary or intrinsic bioreceptivity* of the material (see Section 1.2). Micro-porosity is managed by blending organic waste materials (such as cardboard and coffee) with clay-based mixtures, which disappear during baking, leaving voids or irregularities in their place. These voids and their density determine the intrinsic porosity of the biscuit (fired ceramic material) and vary its surface roughness, influencing its greater or lesser predisposition to bioreceptivity. In addition, this phase also pays particular attention to the structural resistance of the material, modulating the percentages of organic waste filler within the maximum limits above which the material would lose the minimum mechanical properties for the architectural and construction uses it is intended for.
- *Meso-porosity:* Meso-porosity refers to the "architectural" characteristics of the material support, specifically surface geometry and filling. This concept strongly derives from "scaffold design", which, to recapitulate the complexity and heterogeneity of biological tissues, distributes material porosity according to spatial grids, facilitating the integration of cells into the support and the movement of water, nutrients, and spores throughout the volume [64]. Furthermore, if programmed and varied, such meso-porosities can direct cell behavior, establishing areas of greater or lesser biocolonization within the same element and guiding emerging aesthetics and functionalities. In this case, meso-porosity was achieved by applying an additional waste material to the surface of the samples using the impression technique to mimic the random textures of travertine (a typical Roman marble, see Figure 1) and study the influence of surface meso-structures on bioreceptivity (see Section 2.2). In the future, this will enable the creation of variable aesthetics or actual figures by alternating zones of greater or lesser biocolonization enhancement. Among the future directions, the project also envisages the use of digital and computational tools (such as parametric design and 3D printing) to design geometrically defined meso-porosities (see Section 3).
- *Macro-porosity:* Macro-porosity refers to the overall geometry of the object in its final form. It can relate to the overall morphology of the elements or specific surface geometries that can further contribute to the material's ability to retain water, protect

cells from weathering, etc., as demonstrated on various occasions [43,65,66]. In the project at hand, macro-porosity was intentionally uniform for all samples, which were designed as flat square tiles for cladding facades. This choice is justified by the desire to adhere to hologrammatic logic among different levels, which requires a definitive understanding of the lower levels to add additional parameters at the macro level. However, 3D printing will also allow us to create overall morphologies and predetermined geometries in the future.

2.1.1. Study of the Material Support: The White Earthenware

Clays are abundant, widespread, and cost-effective materials compared to other raw materials. Moreover, the industrial and environmental significance of clays and clay minerals arises from their ability to undergo various physical, chemical, and thermal treatments, opening up endless possibilities for future applications, particularly regarding environmental protection [67]. For these reasons, experimenting with the potential bioreceptivity of clay-based constructs can be relevant for the future adoption of this practice in large-scale urban regeneration operations. The term "clay" is often confused with "ceramic", leading to misunderstandings. "Clay" is a natural material composed mainly of fine-grained minerals, generally plastic with adequate water content, and it hardens when dried or fired [68]. This behavior is due to numerous substances recently categorized under "clay minerals" [68]. "Ceramic", on the other hand, refers to a broader category of "non-metallic inorganic materials", which includes cement and refers to the product after drying and firing [69]. For these reasons and to align with scientific terminology, in this article, we adopt the term *"clay-based material"* to indicate any material based on clay minerals with clay-like behavior; the term *"clay-based mixture"* to specifically refer to the plastic compound before firing; and the term *"bisque-fired samples"* to indicate samples fired with an initial and lower-temperature firing phase (usually followed by a secondary firing at a higher temperature when glazing pieces).

Among the clay-based mixtures, we chose white earthenware. This fine-grained, highly plastic material is inexpensive and characterized by a neutral color that can be easily modified using oxides. When fired, white earthenware maintains its porosity (resulting in an approximate water absorption of 8%), unlike other types of clay-based mixtures, such as stoneware and porcelain, which, after firing, assume a vitreous appearance with water absorption below 1% [70]. Moreover, its plasticity makes it suitable for our purposes, as it is easy to manipulate both manually and with additive 3D printing processes. The specific mixture used was purchased from Cibas.sas and is composed of aluminum silicate, calcium and magnesium carbonate, quartz, kaolinite, and illite, with a pH value of 7–8, suitable for biocolonization [25]. During the firing process, especially at high temperatures, clay undergoes various transformations, leading to a more alkaline product, thus increasing the maximum pH to 10. The mineralogical composition of a clay-based material is essential for various reasons and, when combined with different factors related to the firing process, it can strongly influence the physical properties of the resulting ceramic element, such as its bending strength and porosity [71]. An increase in firing temperature and time tends to reduce porosity and increase bending strength because the sintering of clay particles becomes more effective [72]. In addition, porosity can be varied using several techniques that involve blending a clay-based mixture with organic binders that are then burned or decomposed during the firing process to produce porous ceramics or structures with controlled porosity [73,74]. This is experimented with for numerous uses, including sustainable ones, from thermal insulation to gas filtration and membranes [74] to bioceramics for bone tissue engineering [75]. These studies have inspired our project and led to the desire to experiment with the controlled porosity of the final samples to manipulate their bioreceptivity.

In particular, as will be illustrated later, the samples we used underwent only one low-temperature firing (bisque-fire), and we used a limited amount of organic waste to avoid the risk of excessive porosity affecting overall structural properties (see Section 2.2).

2.1.2. Selection of Waste Materials: Coffee Grounds and Cardboard Pulp

Using organic fillers to create porous ceramics is an increasingly important research axis today because it allows for lighter, more performative, cost-effective ceramics. Porous ceramics also offer significant sustainability advantages: from a production standpoint, the amount of clay minerals used is reduced, and firing temperatures are lowered; from a performance standpoint, enhanced thermal and acoustic insulation due to the presence of pores reduces the weight of the building and energy consumption for heating/cooling spaces [76,77]; economically, increased lightweightness reduces transportation and labor costs [78]. The selection of methods to create pores is based on the desired final characteristics, such as the percentage of porosity, pore type, distribution, and size [79]. Among these methods, using pyrolyze wastes as pore-forming agents is most suitable for modifying the micro-porosity of clay-based materials [80] and producing highly porous ceramics [81,82]. Clay-based materials are dried and reduced to powder, then mixed with water and appropriate amounts of waste material (also ground) that are evaporated or burned before or during sintering to create pores [74,83]. This method avoids generating secondary waste by eliminating waste at other temperatures. Furthermore, this methodology is particularly relevant to our project because it allows for the production of an open-porosity material with a high degree of connectivity between pores, providing the material with fluid permeability and the ability to retain high levels of capillary water [84]. This type of porosity is also a target in porous bioceramics for bone tissue regeneration, as it is conducive to cell growth, unlike, for example, insulating porous ceramics that require closed porosity to trap air and gases [84]. Significant is the characterization of secondary materials and the selection of suitable substances to mix, both for the desired type of porosity and pore distribution and to ensure that no volatile substances that could damage kilns and human/environmental health or affect process stability (such as chlorine and sulfur) are produced [85]. Organic waste has been experimented on in recent years, due to the large amount of waste produced by the manufacturing and agricultural sectors and food industries, which are among the main contributors to solid waste [86,87], and because they contain large amounts of carbon and hydrogen that can promote pore formation during firing or sintering processes due to chemical degradation and the corresponding release of gas [88].

In our case, we focused on two types of organic waste: cardboard pulp and coffee. Cardboard pulp is a readily available and widespread waste in the project's reference context (Rome and the Lazio Region, see Section 1). It is economical, easy to burn, non-toxic, and environmentally safe [89]. This choice was also inspired by the Paper Clay technique, which is widely used in Italian workshops because it makes clay-based materials lighter and more plastic, economical, and sustainable. The Paper Clay technique uses plant fibers (cellulose, cotton, or linen) that are homogeneously mixed into the clay mixture, making the material suitable for large-scale applications. Finally, as mentioned earlier, an essential aspect in choosing the waste to use comes from the desired type of porosity and distribution, which influence the overall material's physical properties and, consequently, the bioreceptivity factor. In particular, cardboard pulp consists mainly of cellulose fiber, which, when viewed under a microscope, reveals a complex tangle of tubular microfibers responsible for the compression, stretching, and abrasion resistance of the resulting products and capillary water transport. Mixing waste cardboard pulp transfers this type of "fibrous" porosity to the clay-based material, and it is regularly distributed throughout the mass, giving the material a proper balance between mechanical strength and permeability [84]. The forming processes, such as laying down the clay-based mixture, align these fibers parallel to the stretching direction, forming a layered and lamellar microstructure that is visible even to the naked eye.

To vary the type of porosity and pore morphology, we decided to experiment with a second organic waste, coffee, also considered relevant at the national level and defined as a "novel" ingredient in the circular economy. This waste material has been overlooked but is produced in large quantities yearly and has numerous potential applications [90]. Coffee also does not release toxic substances during firing [85], and it is interesting due to its reduced size and the spheroidal morphology of its granules. The latter is transferred to the pores, facilitating material dispersion in the clay-based mixture, while the small size allows for homogeneous distribution throughout the mass [91]. The fine grain size of coffee also makes it easier to knead the mixture and obtain more homogeneous pastes that can be used with 3D printing, a process made difficult by the fibrous nature of cellulose, which could clog the nozzles (Figure 4). The selection of these two organic wastes allowed us to vary the morphology, distribution, and size of the pores, which, along with the variation in the percentage of waste material used compared to the amount of clay, helped us perform a broad-spectrum investigation into the factors contributing to the bioreceptivity of the material, particularly regarding micro-porosity.

Figure 4. Image depicting the 3D printing test of the clay and coffee-based mixture. The nozzle diameter is 6 mm.

2.1.3. Study of Living Matter and Growth Conditions

As in any other ecosystem, the biocolonization of an inert material occurs through an ecological succession. In other words, a species replaces or succeeds previous biological species over time and in a specific order. As mentioned in Section 1.2, on inert materials, biocolonization begins with species called “pioneers”, which are capable of modifying the chemical environment of the surface and creating conditions for other species to colonize in their place. These species are photoautotrophic organisms [31,32] such as green algae and cyanobacteria, organisms capable of producing the energy needed for survival by transforming light energy into chemical energy [92]. Many of these organisms, like green algae, are “cryptogams”, meaning that they are plants without flowers or seeds that reproduce through spore dispersion in the air, promoting the colonization of surrounding surfaces. Photoautotrophic organisms use solar energy, carbon dioxide, and water to synthesize organic substances that can be exploited for fundamental cellular functions, such as metabolism and respiration. However, despite the simplicity of the fundamental “ingredients” for the growth of these biological species, some optimal environmental conditions are essential to meet. Among these, the type of sunlight that reaches phototrophic organisms is crucial, and it must follow day–night cycles and be indirect, not exceeding 40 lumens of intensity [42]. This means that cells need “niches” to protect them from direct light beams without completely filtering them, and it is essential to place bioreceptive surfaces in shaded areas, especially during the hottest hours of the day. The water content and relative humidity are also important factors to consider, and the growth of microorganisms is generally directly proportional to their constant presence [42].

Furthermore, surfaces should have a set of other nutrients that ensure an overall neutral pH or a pH lower than 10 [93], as well as growth speed, such as nitrogen, phosphorus, and carbon, which, respectively influence protein synthesis (cellular amino acids), nucleic acid synthesis (ATP), and the organic structure of molecule [94]. After the settlement of "pioneer" species, heterotrophic bacteria arise because they can feed on the dead biomass of autotrophs [45]. The bacteria and algae on the rocks enter into a mutualistic relationship, creating a self-sufficient matrix called a subaerial biofilm (SAB). The sediments in the biofilm produce and secrete extracellular polymeric substances (EPS), creating a mucilaginous envelope around the biofilm. This will help bacteria retain water, acquire resistance to environmental conditions, and further adhere to the substrate. Additionally, it will facilitate various bacterial species' entrance into symbiosis with others, creating an ideal pioneer situation [95]. One of the primary SAB organisms is cyanobacteria, such as *Arthrospira platensis*, due to their photosynthesis and atmospheric nitrogen fixation ability. Cyanobacteria have developed protective mechanisms against drying and solar radiation. Also, when there is sufficient water, algae can become one of the SAB organisms. The SAB mainly comprises green algae such as *Chlorella Vulgaris* and *Spirulina* [95–97]. The latter, being more readily available, was employed in this research.

2.2. Experimental Process

2.2.1. Processing Waste Material

Two types of waste material were used to modify the clay-based material's microporosity (or intrinsic porosity). The selection focused on corrugated cardboard (No. 20 PAP), paper (No. 22 PAP), and coffee grounds collected individually from household scraps in small quantities adequate for experimental purposes. As mentioned earlier, the choice of materials was guided by the desire to investigate easily accessible, low-cost waste materials with different microstructures, namely, fibrous and granular microstructures.

The corrugated cardboard and paper were obtained from packaging and envelopes without prints or unique treatments. They were manually broken into small fragments, paying particular attention to removing adhesive residue. The fragmented material was weighed (800 g) and placed in a clean basin, adding room-temperature water to initiate the maceration process to obtain the cardboard pulp. The composition was left in the basin in the laboratory environment (average temperature 25 °C) for 9 days.

As the material did not mature as expected, the cardboard and paper fragments were drained, and water was removed. Heated water (approximately 40 °C) was then added. The fragments were manually worked in immersion in hot water, achieving further fragmentation of the cardboard and paper pieces until reaching the consistency of cardboard pulp. The material obtained this way was left in water inside the basin in the laboratory environment (average temperature 25 °C) for 12 days. The obtained cardboard pulp was subsequently drained, squeezed to remove as much water as possible, and manually fragmented to obtain pieces of equal medium size (spheres ∼1 cm in diameter) (Figure 5).

Figure 5. Processing of waste material (cardboard). From top left to bottom right: fragmentation of paper and corrugated cardboard, checking and possible removal of adhesive material, immersion in water, maceration, reduction to pulp, dehydration, and drying.

The coffee grounds, particularly unblended coffee, were obtained from domestic consumption waste. They were left to dry in a basin for 2 days to remove excess moisture.

2.2.2. Processing Clay-Based Mixtures

A clayey base, specifically white earthenware, was chosen to compose the material substrate. Following the phases generally used to produce porous ceramics [82], the white earthenware was cut into layers and manually fragmented to obtain coarse pieces for better workability. The resulting fragments were placed in a clean basin and left to dry in the laboratory (average temperature 25 °C) for 2 days to obtain dry earthenware. After drying, the fragments were pounded with a mallet to further reduce their size, resulting in smaller fragments and an earthenware powder (Figure 6).

Figure 6. Processing of clay material. From left to right: wire cutting of the earthenware, manual fragmentation, drying, and mechanical fragmentation.

2.2.3. Processing and Baking Clay-Based Mixtures

The composition involved using two types of clay-based mixtures by employing two waste materials to explore various design possibilities. To achieve a clay-based mixture for a porous ceramic, white earthenware was combined with cardboard pulp equal to 4% of the total weight, with the dry weight value being recorded as 2000 g. The clay-based mixture was obtained by gradually adding a moderate amount of water and manually mixing the fragments of white earthenware and cardboard pulp. The clay-based mixture was handworked to achieve a homogeneous consistency. The resulting Paper Clay was then divided into three equal parts, with two parts further enriched with cardboard pulp to obtain additional waste material concentrations of 10% and 20%, resulting in three material samples—A, B, and C (Table 1) (Figure 7). The three Paper Clay samples were divided using the wire-cutting technique, following the artisanal tradition. Three slabs 15 × 15 cm slabs with an average thickness of 0.5 cm were obtained.

Figure 7. Processing of pastes with cardboard pulp. From top left to bottom right: Combination of waste material and clay material, mixing, manual processing, and slabs of samples at different concentrations of waste material.

Table 1. Quantities of ceramic and cardboard pulp used to obtain clay-based mixtures with variable concentrations of waste material (4%, 10%, 20%).

	Sample A	Sample B	Sample C
Clay base	666.7 g	666.7 g	666.7 g
Paper pulp	26.7 g	66.7 g	133.5 g
Concentration (paper pulp/clay base)	4%	10%	20%
Water	as needed	as needed	as needed

In the second phase, the experimentation focused on producing two material compositions using cardboard pulp and coffee grounds. Specifically, this phase aimed to obtain a clay-based mixture with a consistency suitable for 3D printing.

White earthenware, previously fragmented into small pieces, was first divided into four equal parts, each weighing 500 g. These clay bases were then placed in containers to combine the two waste components in two different concentrations, set at 5% and 20%, to obtain four different blends (Table 2). Each mixture was obtained by gradually adding water to achieve a homogeneous and easily workable consistency. The obtained clay-based mixtures were handworked following the artisanal tradition, carefully removing any air bubbles until compact loaves were obtained. The loaves were wire-cut, resulting in two parts for each blend, and later flattened with a smooth kitchen rolling pin to create even surfaces. Slabs that were 15 × 15 cm in size and ahd an average thickness of 0.5 cm were then obtained. The clay-based mixtures described so far formed the basis for our study of micro-porosity and, more specifically, how surface roughness, percentage of porosity, pore type and morphology, distribution, and size influence a material's intrinsic or primary bioreceptivity.

Table 2. Quantities of ceramic and waste materials (coffee and cardboard) used to obtain clay-based mixtures with variable concentrations (5%, 20%).

	Coffee Grounds		Paper Pulp	
	Sample D1	Sample D2	Sample E1	Sample E2
Waste component	25 g	100 g	25 g	100 g
Clay base	500 g	500 g	500 g	500 g
Concentration (waste component/clay base)	5%	20%	5%	20%
Water	as needed	as needed	as needed	as needed

Regarding meso-porosity, i.e., the "architectural" characteristics of the material support, we decided to work on the surface, aiming to create meso-structures and surface irregularities to study their ability to direct biological growth. Following the artistic tradition of leather hardness decoration—identifying the plastic state of the clay that can still be worked—fragments of cardboard pulp were placed on the obtained slabs, covering either the entire surface or half of it. The cardboard pulp was impressed onto the surfaces using a rolling pin and damp cloth, compacting the pressing and preventing the cardboard pulp from losing adherence to the clayey surface. The cardboard pulp was flattened until wholly embedded in the earthenware, avoiding any surface protrusions. This allowed for three types of meso-porosity: without texture, half texture, and full texture.

All the obtained slabs were then stacked on each other, placing wooden slabs in between to prevent possible deformations, and left to dry in the laboratory environment (average temperature 25 °C) for about 10 days to remove excess moisture and provide optimal conditions for the subsequent firing phase. Given the small size of the samples and the desire to influence the porosity as little as possible, the tiles were fired in a Rodhe ST410 kiln in a single firing at 960 °C without glazes. The firing took place automatically with a continuous heating phase until the set temperature was reached, and subsequently, the samples were left to cool gradually (Figure 8).

Figure 8. Processing of pastes with cardboard pulp and coffee grounds. From top left to bottom right: Combination of waste materials and clay material, mixing, cutting into slabs, laying slabs, leather hardening of waste material on the surface, and baking in the oven.

2.2.4. Biological Matter Harvesting

The selection of biological matter was guided by the intention to prepare a laboratory-obtained biological substrate that would allow for its subsequent proliferation or serve as a suitable base to host additional biological matter following exposure to atmospheric agents. Therefore, a biological solution was produced, consisting of spirulina, nutrients, and water within a sterile container, and left in culture for approximately three weeks to increase the quantity of spirulina. Specifically, a home cultivation kit for spirulina, purchased from BioPlankton and including a spirulina culture; a fertilizer with various substances (sodium, carbonates, chloride, nitrogen, phosphor, potassium, magnesium, sulfur, manganese, etc.); and a sieve were used. The kit ingredients were mixed in distilled water with a ratio of 20 g for the fertilizer and 50 mL of spirulina per liter of water, exposed to indirect sunlight at a temperature of 30–35 °C. Subsequently, a setup was created to apply and grow biological matter on the tiles obtained from the firing process.

Two previously cleaned and sterilized plastic basins were prepared and filled with water up to the surface level of the horizontally arranged tiles. A 40-watt light source was positioned parallel to the basins at a distance of approximately 65 cm, with a temporal regulation set by a timer at cyclic intervals of 12 h of light and 12 h of darkness. The previously prepared biological solution was mixed with a cyanobacteria culture and then poured onto the underwater tile surfaces. The spirulina starter, containing vital cells of a single species, does not constitute a significant microbial community for developing the biofilm. This polymeric matrix allows cells to adhere to surfaces and capture water and nutrients. An existing biofilm was collected from travertine slabs partially covering the buildings of the Sapienza University of Rome using a sterilized scalpel and added to the spirulina culture already rich in nutrients for cell growth.

Inside the basins, a mini pump was positioned for water circulation and oxygenation, with careful attention being paid so as to not direct the pump jet directly onto the tile surfaces. Initial observations noted that water circulation via the pump prevented the biological matter from adhering to the surfaces. Therefore, water circulation was halted. The defined cultivation setup was left in the laboratory (average temperature 25 °C) for approximately 20 days (Figure 9). The tiles were removed from the cultivation basins and placed outdoors in partial shade (average temperature 32 °C); they were periodically misted with water for another 20 days.

Figure 9. Cultivation set for spirulina. The bisque-fired samples were placed at the water level, and a symbiotic culture of spirulina and cyanobacteria was spread on their surfaces.

2.3. Validation Experiments

The validation experiments aimed primarily to establish basic guidelines for implementing future experiments for designers interested in exploring organic waste as a design element for bioreceptivity. Specifically, they were guided by the desire to investigate, through an iterative and recursive process inherent in RtD methodologies and material experimentation, how the micro-porosity and meso-porosity induced by pyrolyzed organic waste influence biocolonization. This could allow the designer to act as a "choreographer" of biological growth, fostering new aesthetic and functional applications and catalyzing sustainable innovation management. In particular, regarding micro-porosity, two aspects were considered, the importance of which was described earlier:

1. *The intrinsic porosity of the material and how the type of pores influences it:* This was validated by calculating the percentage variation in weight of the clay-based material mixed with organic waste and fired compared to the weight of a "target" sample, characterized by the exact dimensions (15 × 15 × 0.5 cm) but with an entirely white clay mixture. The dry weight variation is a valid and easily understandable measure for assessing how much the organic waste-induced porosity is directly proportional to the percentage decrease in the sample's weight compared to the target value.
2. *The subsequent permeability of the material and its ability to retain capillary water inside* was calculated by measuring the weights of the samples at different states and comparing them with the dry weight. As the first value, the percentage increase in weight after immersing the samples in water for two minutes was calculated. This allowed us to study each material's ability to absorb water, i.e., their permeability. Subsequently, the samples were left to air-dry at room temperature and weighed on three other occasions: after 30 min, after 1 h, and after 3 h. This was carried out to estimate each material's water retention capacity, i.e., their ability to retain water. The choice of these methods and timings derives from the desire to simulate a real context where weather conditions such as rain can wet the clay-based materials and allow water to run off before the sun and heat dry them. This point also helps us understand whether

and how meso-porosity affects permeability and water retention despite its primary purpose being to create niches favorable to cell deposition.

Finally, growth patterns from the 40 days of attempting to create a biofilm on the surface were analyzed to investigate the holographic relationship between the two levels and how this affects the permeability of the different samples to biological growth. Specifically, the samples were photographed individually with the lens perpendicular to the surface. As it was impossible to determine the biofilm coverage through a comparison with pre-growth images due to differences in light intensity and proportions, each image was adjusted by minimizing brightness and saturation for "previous" images and maximizing them for "subsequent" images using Adobe Photoshop CC 2023 tools. This highlighted the green parts of biological growth. Subsequently, with the same program, differences between the two levels of image overlay were highlighted through the "differences" layer blending option [98]. The resulting images could have been immediately used to analyze growth patterns qualitatively. However, to obtain quantitative data on the percentage of biofilm coverage, the resulting images were exported to ImageJ (version 1.8.0) [98]. In ImageJ, the images were first converted to 8-bit grayscale (Image > Type > 8-bit) and then to black and white bitmap (Image > Adjust > Threshold > B/W > threshold set at 40). The percentage of white pixels was then calculated to indicate the percentage of the sample's surface covered (Analyze > Measure). Although this comparison cannot entirely correspond to reality, it can be an excellent starting point for initial considerations.

3. Results and Discussion

The results obtained from the validation phases have allowed us to take a step forward in understanding the subtle relationships among the numerous parameters influencing the bioreceptivity of a clay-based material "enhanced" through porosity induced by sacrificial and pyrolyzed organic waste. To achieve these results, 20 samples based on clay-based blends were created and enriched with two types of waste materials (cardboard and coffee) used at different concentrations (4%, 5%, 10%, 20%), along with varying surface geometries (planar, half-textured, and full-textured), making a total of 15 different types. Out of these, 11 were selected and compared (Figure 10). The selected samples presented a higher textural quality, both in meso-porosity (in terms of level of definition and detail) and blend compactness. We assume that the observed disparities in blend quality could be ascribed to the distinct processing methodology employed, characterized by manual crafting in accordance with traditional artisanal techniques.

3.1. Micro-Porosity

1. *The Intrinsic porosity of the material and the influence of pore type:* In Figure 11, the graph depicts the percentage variation in weight of each sample (1–11) after firing and drying compared to the weight of a "target" sample made of pure white earthenware (223.44 g). Firstly, from the comparison, we can easily infer that, with the increase in the percentage of organic waste mixed with the clay-based mixture, the weight loss in the samples is more significant, increasing porosity. This holds for both samples mixed with cardboard and those mixed with coffee. From the comparison between the two, we can deduce that the weight loss is slightly lower in the samples treated with cardboard. This is probably due to the morphology of the pores and the volatile substances resulting from the respective wastes: The fibrous porosity of cardboard occupies a slightly lower density than the granular porosity of coffee. At the same time, the latter releases a greater quantity of carbon during firing [88]. However, optimal results were achieved with both wastes, with weight losses up to 37.43%.

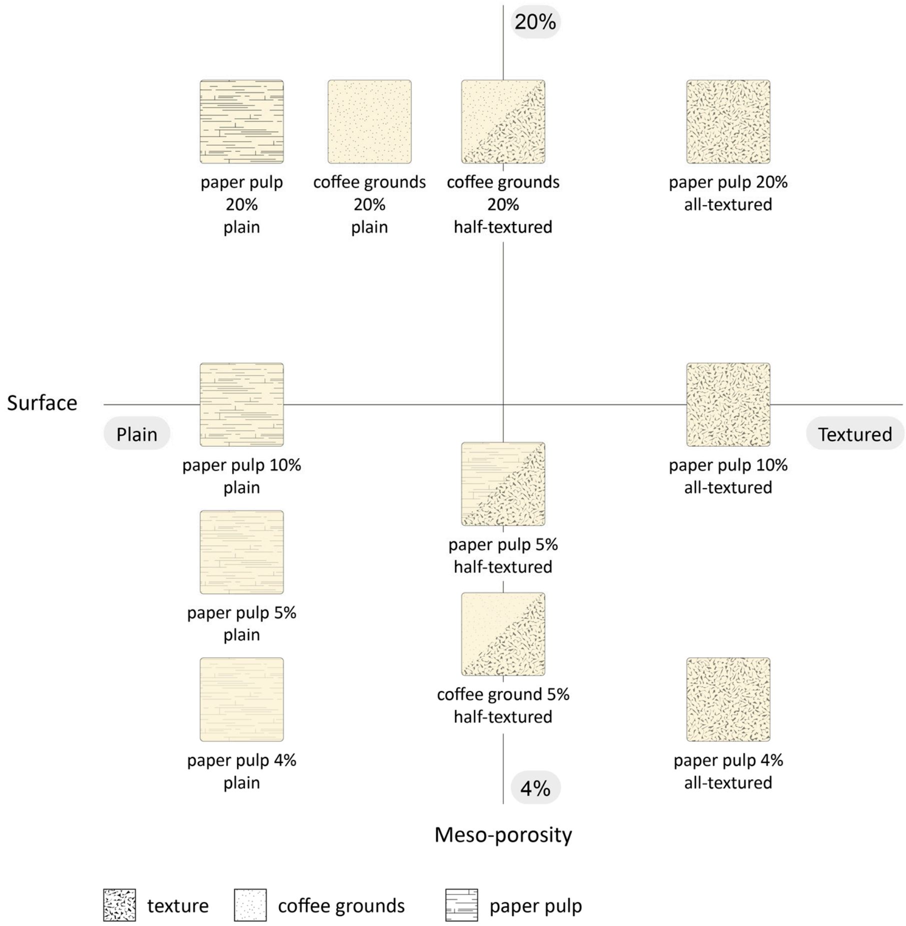

Figure 10. Classification diagram of samples based on surface type and level of meso-porosity.

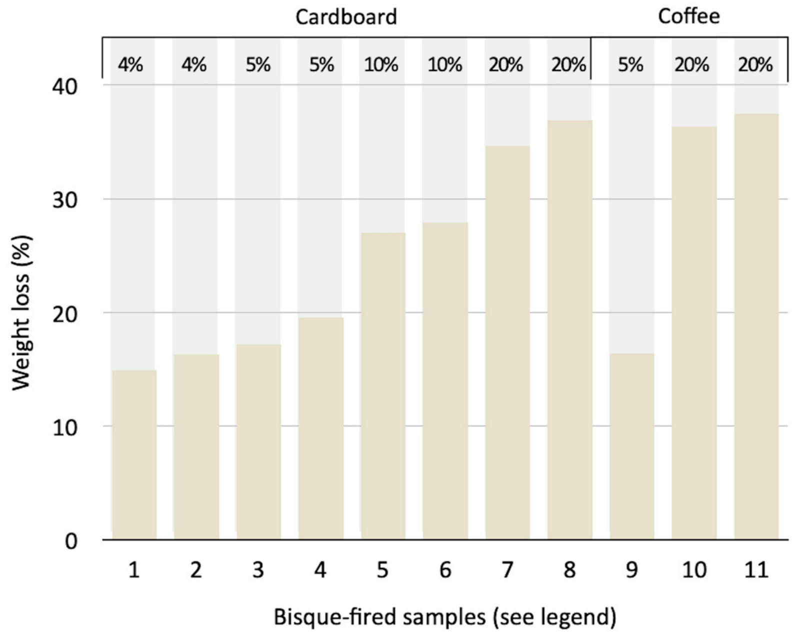

Figure 11. Weight loss in relation to a "target" sample made of pure earthenware. Legend: (1) Paper pulp 4% plain; (2) paper pulp 4% all-textured; (3) paper pulp 5% plain; (4) paper pulp 5% half-textured; (5) paper pulp 10% plain; (6) paper pulp 10% all-textured; (7) paper pulp 20% plain; (8) paper pulp 20% all-textured; (9) coffee ground 5% half-textured; (10) coffee ground 20% plain; (11) coffee ground 20% half textured.

2. *Fluid permeability and water retention:* In Figure 12a, the graph shows the percentage variation in weight of each sample (1–11) compared to the dry weight after various phases: (1) 2-min immersion (beige) and the subsequent (2) 30 min (green), (3) 60 min (orange), and (4) 180 min (red) of air-drying under ambient conditions. From the analysis of the percentage increase in weight after the immersion phase (Figure 12b), we can infer that the weight increase is directly proportional to the quantity of organic waste used and, therefore, porosity for both coffee and cardboard pulp. Furthermore, the latter seems to provide more excellent permeability to the material, again justifiable by the morphology of the pores, which, by creating actual channels for water flow, can promote its absorption and "trapping". However, in the drying phase (Figure 12b–e), coffee appears more performative because the channels created by the waste paper's fibrous structure also facilitate the outward water flow.

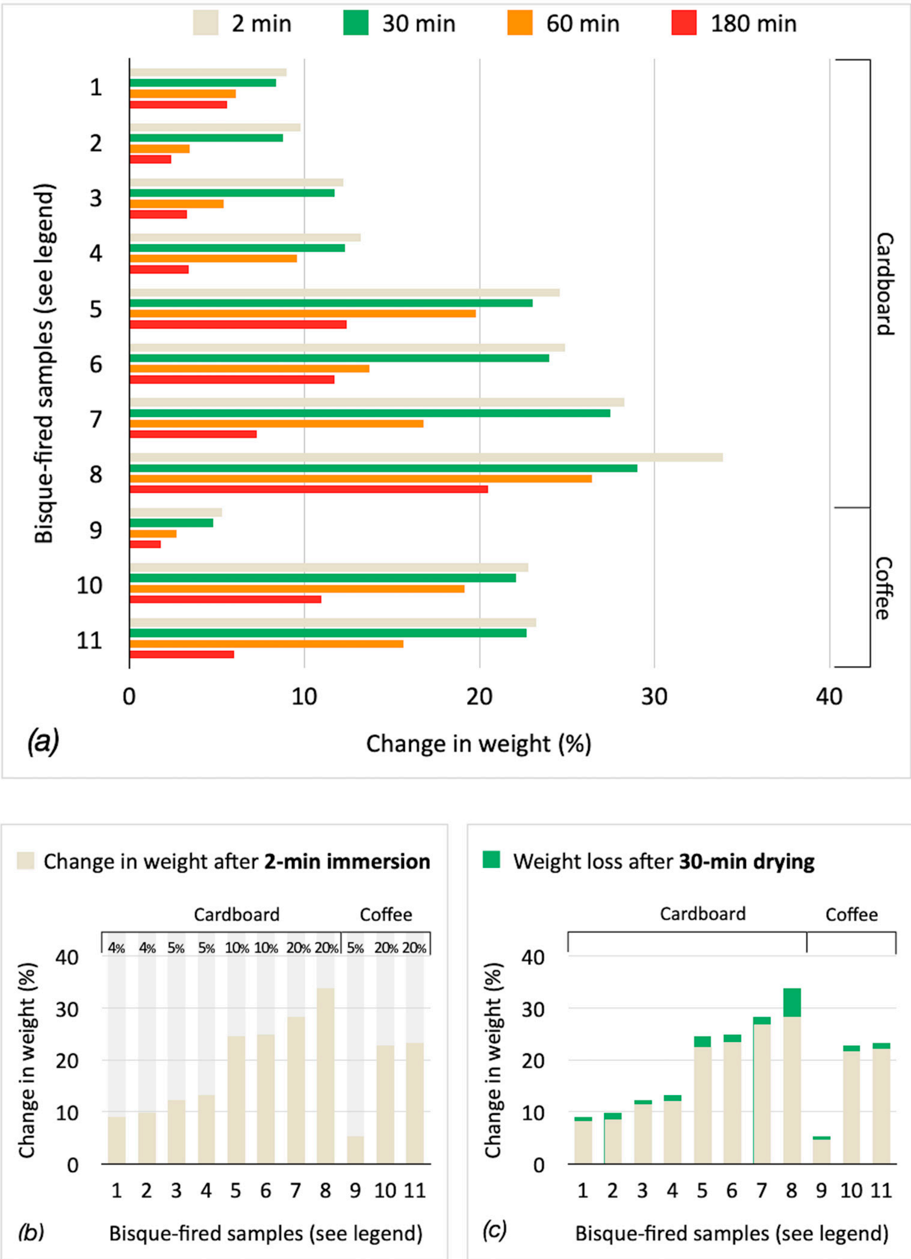

Figure 12. *Cont.*

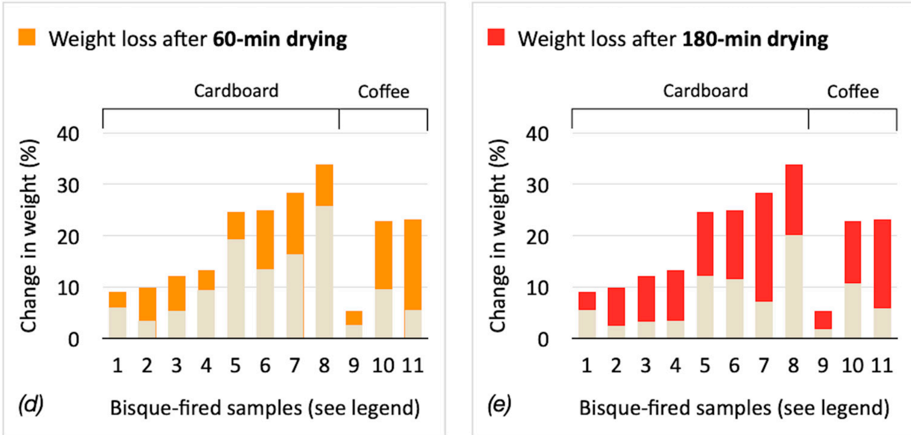

Figure 12. (**a**) Percentage variation in weight of each sample (1–11) compared to the dry weight after various phases: (1) a 2-min immersion (beige) and the subsequent (2) 30 min (green), (3) 60 min, and (4) 180 min of air-drying under ambient conditions. (**b**) Percentage variation in weight of each sample (1–11) compared to the dry weight after a 2-min immersion. (**c**) Weight loss of each sample (1–11) compared with "wet" weight after 30 min of air-drying. (**d**) Weight loss of each sample (1–11) compared with "wet" weight after 60 min of air-drying. (**e**) Weight loss of each sample (1–11) compared with "wet" weight after 180 min of air-drying. Legend: (1) Paper pulp 4% plain; (2) paper pulp 4% all-textured; (3) paper pulp 5% plain; (4) paper pulp 5% half-textured; (5) paper pulp 10% plain; (6) paper pulp 10% all-textured; (7) paper pulp 20% plain; (8) paper pulp 20% all-textured; (9) coffee ground 5% half-textured; (10) coffee gr. 20% plain; (11) coffee ground 20% half textured.

3.2. Meso-Porosity

1. *Intrinsic material porosity and the influence of pore types:* From the graph in Figure 12a–e, essential considerations can also be made regarding surface meso-porosity. In particular, we can confirm that its primary role is not the creation of greater porosity. Comparing the results of samples with the same amount of organic filler but with different surface conformations (1–2, 3–4, 5–6, 7–8, 10–11), we can see that the % weight variation is negligible, hovering around one percentage point.
2. *Fluid permeability and water retention:* In the graph in Figure 12e, the quantity of absorbed and trapped water in different pairs of materials with different surface conformations is also compared. In particular, an unexpected result can be deduced: samples without meso-structure (1, 3, 5, 10) retain water inside them for a longer time compared to others. Even though no significant variations were observed in the first 30 min, as time passed and the water began to evaporate, the textured samples experienced a more significant average weight reduction. This is probably because the water is not "trapped" as in the pores and tends to evaporate more quickly, although this is partly offset by the absorption of "stagnant" niches over time. Finally, we can observe that in the case of textured samples, coffee accelerates weight loss; this is because, being inherently less permeable, it takes more time to absorb the "stagnant" niches, losing water through evaporation.

3.3. Hologrammatic Principle

Figure 13 presents biological growth patterns and their respective coverage percentages. From this analysis and the information above, we can derive some fundamental guidelines for upcoming experiments and the development of aesthetic and functional components that leverage the design of the bioreceptivity rate to create gradient surfaces and properties:

1. **Meso-porosities primarily serve as cell deposition niches, allowing for biofilm growth intensity to be established** by varying its depth and intricacy. These niches provide accommodation for cells and shelter them from external factors (such as

high solar brightness), promoting their proliferation (see all samples, especially (a,b), (d–f), (h)). It has been shown on other occasions that physical characteristics, such as the surface inhomogeneity of materials and the presence of niches, have a more significant influence on bioreceptivity than chemical properties [98,99]. These factors create an optimal microclimate for anchored cells, accumulating water, dust, shade, and nutrients [40]. This aspect could be significant for forming future 3D-printed meso-structures with specific morphologies and depths to coordinate biological growth as desired. The team is already conducting preliminary experiments in this direction.

2. **The guidance for cells provided by meso-porosities can be amplified at the micro-porosity level,** where varying the quantity and type of intrinsic material pores can influence fluid and nutrient permeability and retention. In particular, increasing the quantity of waste also increases biological coverage (see all samples, especially the different coverages of samples (a) and (d), (f) and (g), and (h)). However, factors of final product strength, especially in structural elements, must be considered and are inversely proportional to the quantity of waste.
3. **Micro-porosity offers exciting insights into surface roughness,** which can be exploited to enhance cell adhesion and create subtly shaded areas of green. For example, the growth rate is high in samples augmented with coffee waste, even if not very visible (see sample (g)). This is because the waste's granular morphology makes the surfaces rougher and filled with micro-niches to which cells easily adhere. Material roughness and porosity provide better adhesion for organisms, whilst porosity and micro-groove formation affect water retention [39].
4. **The quantity of absorbed water is not directly proportional to biological growth.** In some cases, such as in samples (c) and (e), the high absorption and retention water rates are not compensated by the desired growth pattern and coverage. Water retention likely influences this aspect: water needs to wet the material support but not stagnate for too long to allow microorganisms to interact with cells and form a biofilm. This explains why coffee-based samples show higher growth potential, as they can flow water more rapidly, retaining only the necessary moisture (see samples (f), (g), and (h)). This result is consistent with other research addressing the issue of water access and retention in bioreceptivity. The latter acts as protection against fluctuations in environmental conditions and solar radiation, as well as impacts on the extension of vegetative life [95], while the water flow is crucial for its capillary movement across surfaces and reaching potential hotspots where microclimates can benefit from excess quantities [43,66].
5. **The size of niches should be manageable.** In addition to depth, the size and morphology of niches are essential parameters. Smaller and open niches demonstrated more excellent permeability to biological life. They can more effectively "trap" cells and prevent them from washing away with water or air. This is evident in sample (a), where the large and shallow irregularities did not result in high green concentrations, and conversely, in sample (g), which, despite low visibility, has the highest biological coverage percentage. However, this aspect is not considered a problem to overcome but rather an additional opportunity to vary bioreceptivity rates through design.
6. The results of this research work align with similar research works investigating the role of micro-, meso-, and macro-porosities on materials' bioreceptivity. The work of Cheng and Lharchi [66], for example, investigated the role of macro-form, micro-grooves and material porosity in 3D-printed ceramic structures, finding that micro-grooves given by the layer-by-layer stratification make up an area of high-growth potential due to high water and nutrient retention, while the overall 3D-printed geometries affect the creation of microclimates and the water flow's direction. Mustafa et al. defined design guidelines for meso- and macro-geometries affecting bioreceptivity, highlighting, as in this research work, the hologrammatic correlation between scales [43].

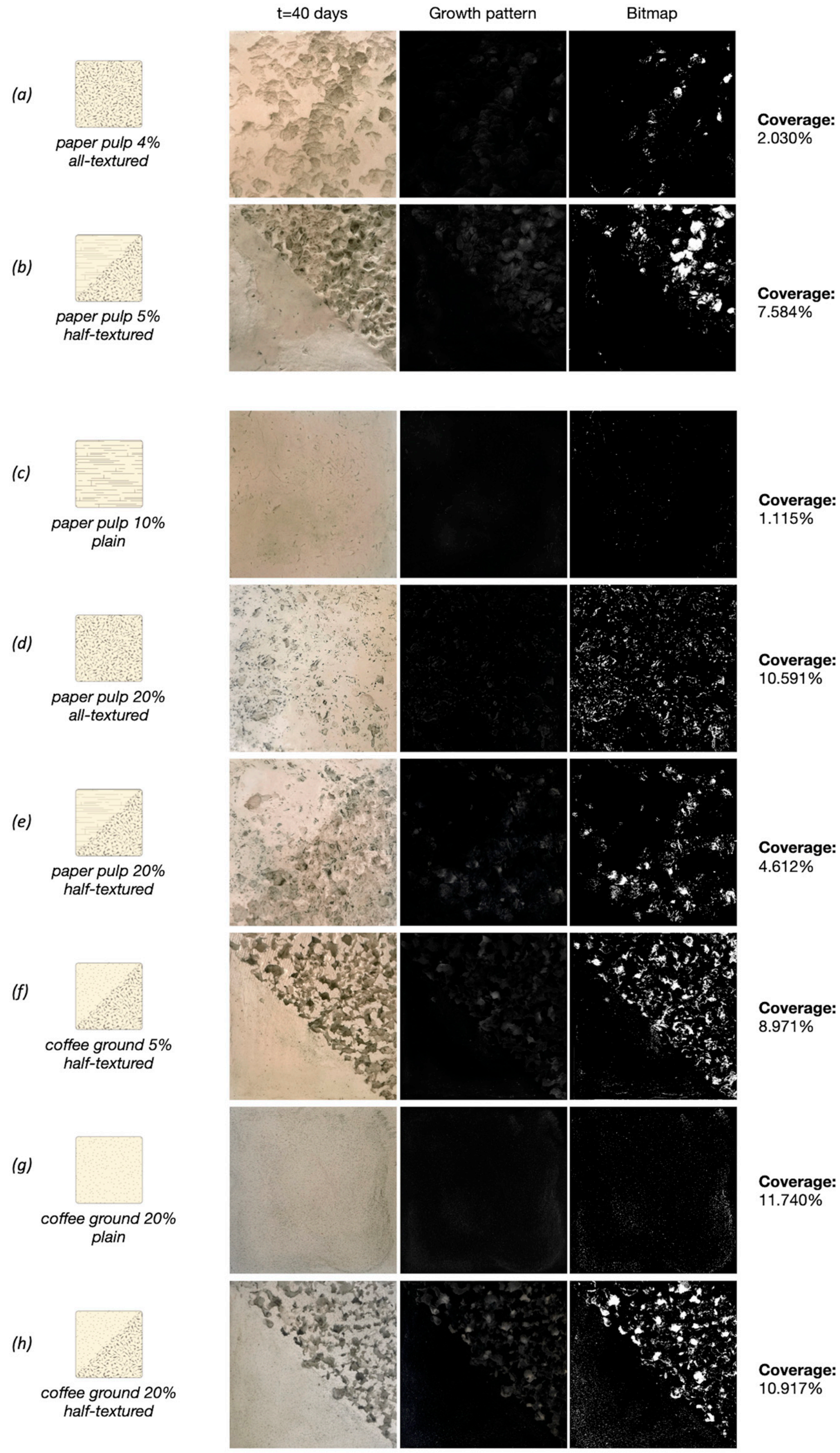

Figure 13. Biological growth patterns and their respective coverage percentages.

These results also inspire the enhancement of the research conducted so far using 3D printing, adding a third level of macro-porosity—previously intentionally kept consistent across all samples—to our experiments.

4. Conclusions

This paper explores new scenarios of bio-integrated architecture as a means for symbiotic futures between humans and nature. It delves into how design can facilitate this transition by using bioreceptivity for urban regeneration, particularly focusing on clay-based materials and organic waste management to achieve controlled bioreceptivity.

Leveraging an RtD approach, the described research promotes circularity by using waste materials such as cardboard pulp and coffee grounds, which are easily accessible and present on-site. They are integral to every stage of the project's development, serving as a cornerstone in creating the final product, akin to scaffolding in biofabrication. This subtle yet tangible utilization of waste materials aims to reshape users' perception of them, showcasing their ability to "augment" the properties and aesthetics of the surrounding materiality. This approach redefines the notion of "sustainable material", emphasizing its inherent qualities and broader significance within the system.

Furthermore, the built environment's dominant aesthetic resemblance to nature serves a practical design goal of "drawing" with "green" on the existing city, creating a new layer that is not only aesthetically pleasing but also contributes to improving the environmental conditions of the intervention area, such as air quality and water pollution.

The following steps will involve identifying and utilizing the tested geometries to design tiles with different habitability areas, indicating zones more or less suitable for the development and growth of microorganisms. The aim is to incorporate images, toponymy, and signage on the surfaces of buildings, offering a new medium for urban art and wayfinding. For this purpose, moss, algae, and cyanobacteria could be involved as welcomed guests to create a controlled "*tableau vivant*" within the city, demonstrating the practical application of the research findings.

This research aligns with Responsible Research and Innovation (RRI) principles, emphasizing collective decision making that considers environmental impacts. It underscores that environmentally conscious projects are multifaceted endeavors, encouraging reflection on cultural implications stemming from contemporary scientific and technological progress.

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