ABSTRACT: Human Evolution – from Stone Age to Silicon Age – has always been connected to the prevailing material of each era. With biofabrication the matter of the project becomes alive changing our material world, the figure and role of designers – who learn to interact with nature as co-workers – and their relationship with processes and industry.

Analysing emergent phenomena and trends we can outline a projection of how a possible future could be if we prove to be able to grasp and amplify them, as well as of what could happen if we keep on ignoring them. The research questions how design places itself in the transdisciplinary field of biofabrication, how far its range expands and which are indeed its limits, with the aim of understanding to what extent biofabrication is transforming designers' approach, activity, scope and cultural framework. Furthermore, it questions which is the specific contribution of design in fostering the application, appreciation and consequent diffusion of biofabricated materials within a timeframe appropriate to the urgencies of the contemporary world. This means to bypass the long lead times characterising the industrial development of new materials, to make them rapidly and easily available through everyday objects, thus playing an active part in such design driven material revolution.

After tracing the theoretical framework, the research proceeded with a hands-on experimentation carried out in two stages: the *basic experiments* useful to gain an understanding of different materials and processes in the biodesign field, learn how to interact with organic and living matter, and develop a methodology which suits the hybrid dimension between design and biology; the *fermentation experiments* where the proposed methodology is applied to one specific material with an in-depth experimentation on microbial nanocellulose. The fermented material is explored shifting from the micro to the macro scale: from process to material, from product to system. Design approaches biofabrication acting on multiple scales thanks to its envisioning ability: it can intervene on material properties as vehicle for sensations, emotions and meanings, develop application scenarios able to valorise and communicate such properties, but also new production-consumption systems which take into account the systemic interconnection each material and product has with environment and society.

Biofabrication is giving us the chance to act a radical change of frame and rethink the way we produce and consume, and more generally the way we live and relate to the Earth habitat through our behaviours – strongly entangled with and influenced by materials, resources and processes we use. We have the responsibility, and opportunity, to shift from a *parasitic* to a *mutualistic* attitude as a species, move from the linear mechanistic idea of *progress* and incremental growth – based on consumption and exploitation – to the rhizomatic organicistic idea of *evolution* – based on use and collaboration –, discarding the twentieth-century anthropocentric mindset and establishing a symbiotic co-existence among all planetary systems.

PhD Planning, Design, Technology of Architecture

PhD CANDIDATE Lorena Trebbi

Evolving Matter

Sapienza Università di Roma | Sapienza University of Rome | ciclo cycle XXXIII | nov. 2017 - mar. 2021
Scuola di Dottorato in Ingegneria Civile e Architettura | Doctoral School in Civil Engineering and Architecture
Dipartimento di 'Pianificazione, Design, Tecnologia dell'Architettura' | 'Planning, Design, Technology of Architecture' Department

Sapienza
Università di Roma

Dottorato di Ricerca PIANIFICAZIONE, DESIGN, TECNOLOGIA DELL'ARCHITETTURA
PhD PLANNING, DESIGN, TECHNOLOGY OF ARCHITECTURE
Coordinatore | Director
Prof. Fabrizio Tucci

Curriculum DESIGN DEL PRODOTTO
Curriculum PRODUCT DESIGN
Coordinatore Curriculum | Curriculum Chair
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Evolving Matter

the future of materials and design in the biofabrication era

Dottoranda | PhD Candidate Lorena Trebbi
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UNIVERSITÀ DI ROMA

PHD
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DIRECTOR
Prof. Fabrizio Tucci

CURRICULUM
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CURRICULUM CHAIR
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EVOLVING MATTER

the future of materials and design in the biofabrication era

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Lorena Trebbi

SUPERVISOR
Prof. Sabrina Lucibello

CYCLE XXXIII
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Introduction

The current environmental crisis and the broken relationship we established with the planet prompts the question: what sort of future awaits us? Which materials, artifacts, resources and systems will populate the planet in fifty years?
Biofabrication is offering us an opportunity to radically change the way we interact with the Earth ecosystem, and designers are urged to take action and play their part. The dynamic exchange between design and science has proved particularly fruitful, leading us to understand the functioning of Nature – of which we are an integral part and not something separated from it – and learn how to adapt to the cyclical nature of its metabolism rather than try to stand against it, by replacing the idea of progress with the one of evolution.
The designer – which always acted as mediator between research and society – is now aware of playing a crucial role. The impact design has on everyday life behaviours, determines on the large scale our collective behaviour as society, and designers must exercise such ability consciously.
We should grasp the technological opportunities provided by biofabrication, in order to re-think the world we inhabit starting from matter and processes through which we shape it. We should not just search for circular materials, nor focusing on individual and partial point of views. We need to shift our scope of *refl-action* from micro to macro, expanding such technological revolution to the cultural sphere and pushing our material culture towards radical and systemic changes.

PART I

Future Perspectives

The future is not a predefined destination,
a separate space or time

The future is a
multiplicity of ideas, critiques and potentialities that are
embedded in the narratives, objects
and practices of our daily lives

In this sense, multiple, often conflicting, futures are always
already here as part of a continuously unfolding present
and past

Kjaersgaard, Halse, Smith, Vangkilde, Binder & Otto

CHAPTER 1 SYMBIOSIS
FROM PARASITISM TO MUTUALISM

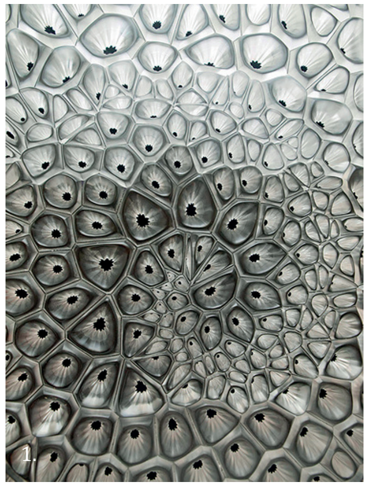
ABSTRACT

With the evolution of the idea of sustainability within the design culture, the design activity has been gradually shifting from punctual interventions on single products to a more holistic approach. Beside products, designers started to look at materials, processes and systems, broadening their scope. Our industrial system, however, still remains grounded on a linear model, result of an anachronistic conception of the world careless about new discoveries and awarenesses characterising contemporary society. We keep on consuming all resources available in a linear way rather than using them circularly, implementing an approach which is destructive instead of regenerative. All approaches towards ecology, sustainability and environmental issues until now indeed, always acted isolating one of the aspects characterising the same issue, facing them as something separate from one another. It is now clear that such attitude is inconclusive in addressing today's complex issues, highlighting the fact that we need structural changes in our production-consumption systems, which have to be grounded on the awareness that we are operating among open interconnected systems.
Such structural changes will require a radical change of frame also in the cultural sphere, through which discarding the values of competition and dominion and embracing the ones of interdependence and collaboration. We need to abandon the old-fashioned cosmetic environmentalism, since it operates within the same system which is cause of the problem, legitimising it. To shift from the parasitic symbiosis, characterising our current relationship with the planet, to a mutualistic one, we have to overcome the dichotomic contraposition between humans and nature, and realise that we are just part of it.

1.1 Ecology and Design: first steps

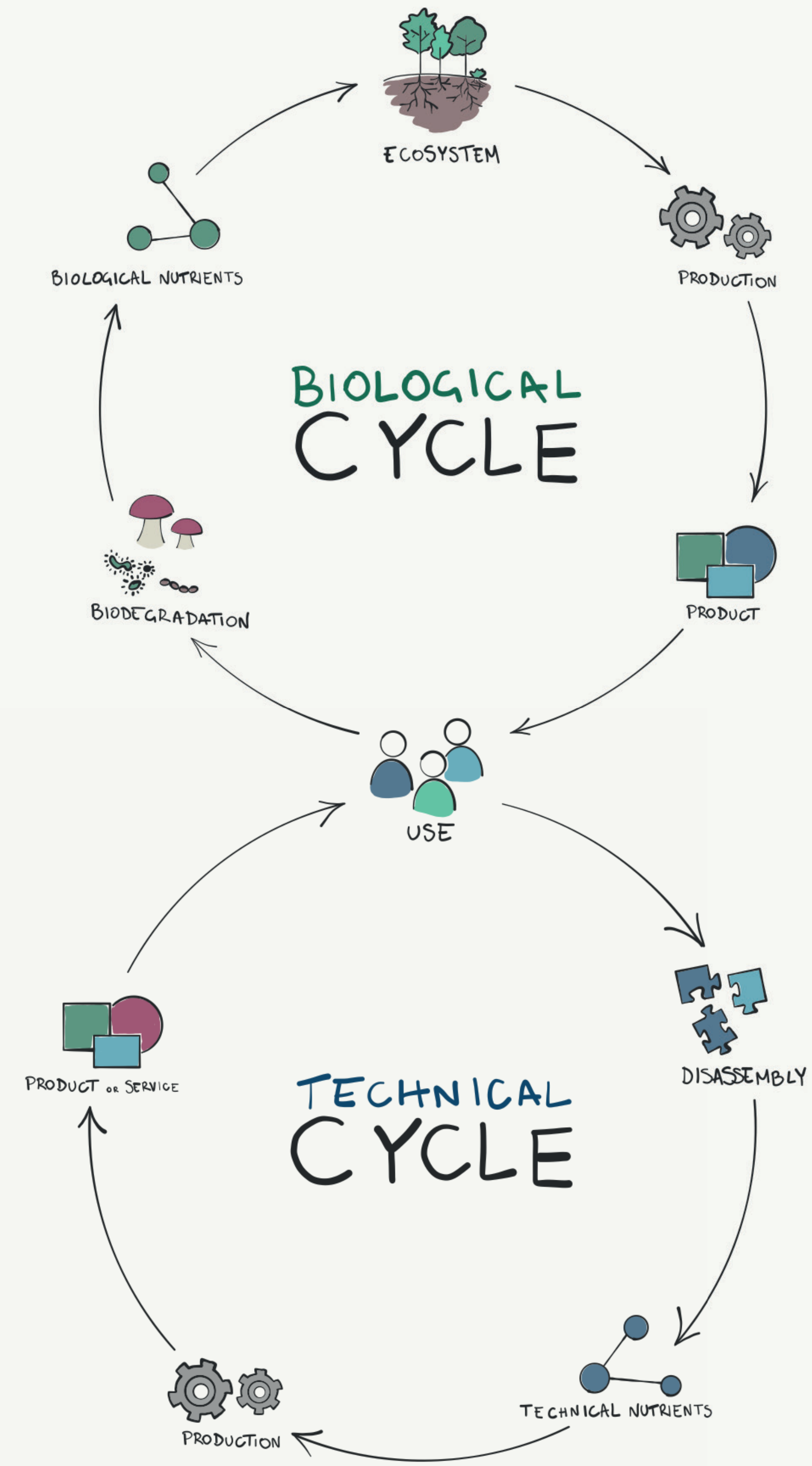
Within the design culture, the first environmental considerations were made by Victor Papanek who highlighted the huge social and environmental impact of design, and then its moral and social responsibilities. He stated that "the designer is powerful enough to put murder on a mass production basis" (Papanek, 1971)[1]. The design of each single product indeed, has consequences on the wide scale, which go from the environmental ones related to life-cycle, resources and disposal, up to the social ones such as determining the working conditions of the people who is going to produce that product. History teaches us that designers, engineers and producers have often employed harmful or toxic materials in architecture and design projects with no concern of their effects, spreading them globally. That's what happened with asbestos for construction purposes, lead for printing inks or pencils, and is still happening today with the employment of plastics for disposable products, which are accumulating, breaking apart and contaminating waters worldwide.
In practice, however, the disruptive approach proposed by Papanek was not actually applied in the design practices. The first steps in that direction were made with green design, but were focused on the single product rather than on the overall design approach. Green design tried to decrease the environmental impact through punctual interventions on the individual features of each single artefact. If was followed by the reuse-reduce-recycle paradigm, aimed at reducing the amount of material used, facilitate the disassembly and reuse elements of discarded products to make new ones, and to employ recycled or recyclable materials. Later, in the second half of the 90s, such approach was broadened to address the entire product life cycle, from resources extraction to product disposal. So, with a life-cycle approach green design evolved into ecodesign, supported by life-cycle assessment (LCA) methods which allowed the quantification of environmental impacts from a technical perspective, but still with limited attention to the human-related aspects.
Between late 1990s and early 2000s design researchers started to look at nature as a source of inspiration to address su-

1. The design of a product determines several aspects which go far beyond the scope of its use such as the way it is produced, and therefore the kind of factory, where this factory is located (with consequences on the urban environment), where and how the facroty workers live (with consequences on housing and society). But its influence is not limited to the production stage, affecting through the objects that we use our behaviour and our interaction with the environment, hence the great social and moral responsibilities of designers



1. Neri Oxman, Stalasso, example of biomimetic design wich reproduces natural mineralisation processes
2. Cradle-to-Cradle: technical and biological metabolic flows

stainability, with a greater focus on processes and productive systems rather than on single products. Is the case of biomimicry (Benyus, 1997), through which transfer the efficiency of nature's solutions to the human-made world, looking at nature as a model and ecological standard to which to refer. Starting from this concept, the Cradle-to-Cradle approach (Mc Donough & Braungart, 2002), puts the focus on the flows of material and resources, suggesting a regenerative approach for the industrial model as opposed to the exhaustive one that we developed so far.
In each of these approaches, all the social aspects related to the use of products, are completely disregarded, despite the user-product relationship can influence many aspects such as energy consumption or durability. Therefore, emerged new approaches as the emotionally durable design, to overcome the psychological obsolescence and allow the user to create an emotional bond with the product; or the design for sustainable behaviour, in order to intervene on the way users interact with the product through affordances and constraints. And yet, in these cases too the intervention was limited to the dimensional scale of product innovation, necessary but not sufficient condition to introduce radical and far-reaching changes, offering once again "symptomatic" solutions unable to tackle the deeper roots of the problem.
From the late 90s then, designers started to move towards wider approaches taking into account the interconnection among environmental, social and economical systems, as in the case of product service systems (Thackara, 2005; Ceschin & Gaziulusoy, 2016), and design for social innovation (Manzini, 2015).



2.

From cradle-to-cradle

Technical and biological metabolic flows

“Cradle-to-cradle: remaking the way we make things” is a book by the German chemist Michael Braungart and the US architect William McDonough, where they propose a third way to face the problem of resources consumption and ecosystems’ destruction, as an alternative to the dichotomy development/ sustainability.

Still today the industrial system is based on the linear model – from cradle to grave – resulting from a conception of the world which belongs to the past, careless about new discoveries and awareness about interconnection and complexity of the system in which it is inserted. Industry and its infrastructures are designed to pursue economical growth, at the expenses of health, environment, natural and cultural richness. This approach determines what Braungart and Mc Donough define “intergenerational remote tyranny” that is the tyranny exerted upon future generations as a consequence of actions implemented today.

From the book’s publication in 2002 until today, we had the chance to see with our own eyes and experience first hand what this means, with the many environmental disasters which have been hitting our planet.

The only efforts which have been made in this regard were solutions aimed at damage reduction, which do nothing more than make matters worse: make things “more sustainable” or “a little less damaging” has only resulted in making the problem less visible, maintaining the same model instead of pushing for change. This approach – eco-efficiency – acts only a greenwashing promoting a cosmetic environmentalism. It operates within the same system which is cause of the problem and is limited to slow it down, offering the illusion of change without actually creating the conditions under which it can occur.

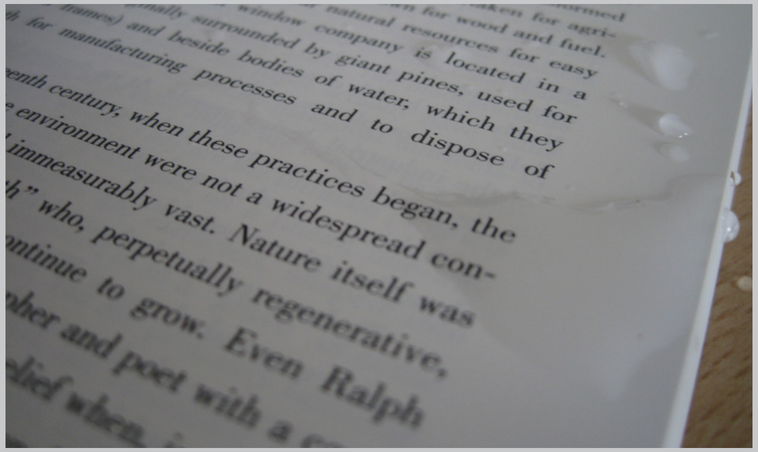
As Morin explains with the concept of “ecology of action” (2002), any action undertaken escapes the intentional control of the subject who implements it, and therefore any process brings secondary unexpected effects. This because we are part of complex open systems, and therefore is necessary to broaden our vision and look at the overall context rather than at single processes, products or actions.

In order to radically change the current consumptive production system we need to shift from the linear cradle-to-grave model, which follows the paradigm take-make-discard subtracting resources and returning waste, to the circular model from cradle-to-cradle adjusting to the functioning of the planetary ecosystem.
Nature indeed, operates through a metabolic system where waste equals food and therefore he waste itself no longer exists, since waste from a system becomes nutrient for another one and so on (carbon dioxide emitted by animals is a nutrient for plants which use it to grow etc.).

On the other side humans implemented an industrial system where raw matter is extracted from hearth and then altered in a way which doesn’t allow to give nutrients back to the environmental system as as it should.

However we can now distinguish between two different nutrients flows: biological nutrients which can be returned to the biosphere with no harm but rather nourishing it, and technical nutrients that we can return to the technosphere, designing productive systems through which they can be recirculated within the technical metabolism. In this context the worst case scenario is represented by the so-called “monstrous hybrids”: a mix of organic and technical materials, neither of which can be retrieved at the end-of-life of the product (a condition that occurs in the majority of the products around us, from the shoes we wear to the books we read).

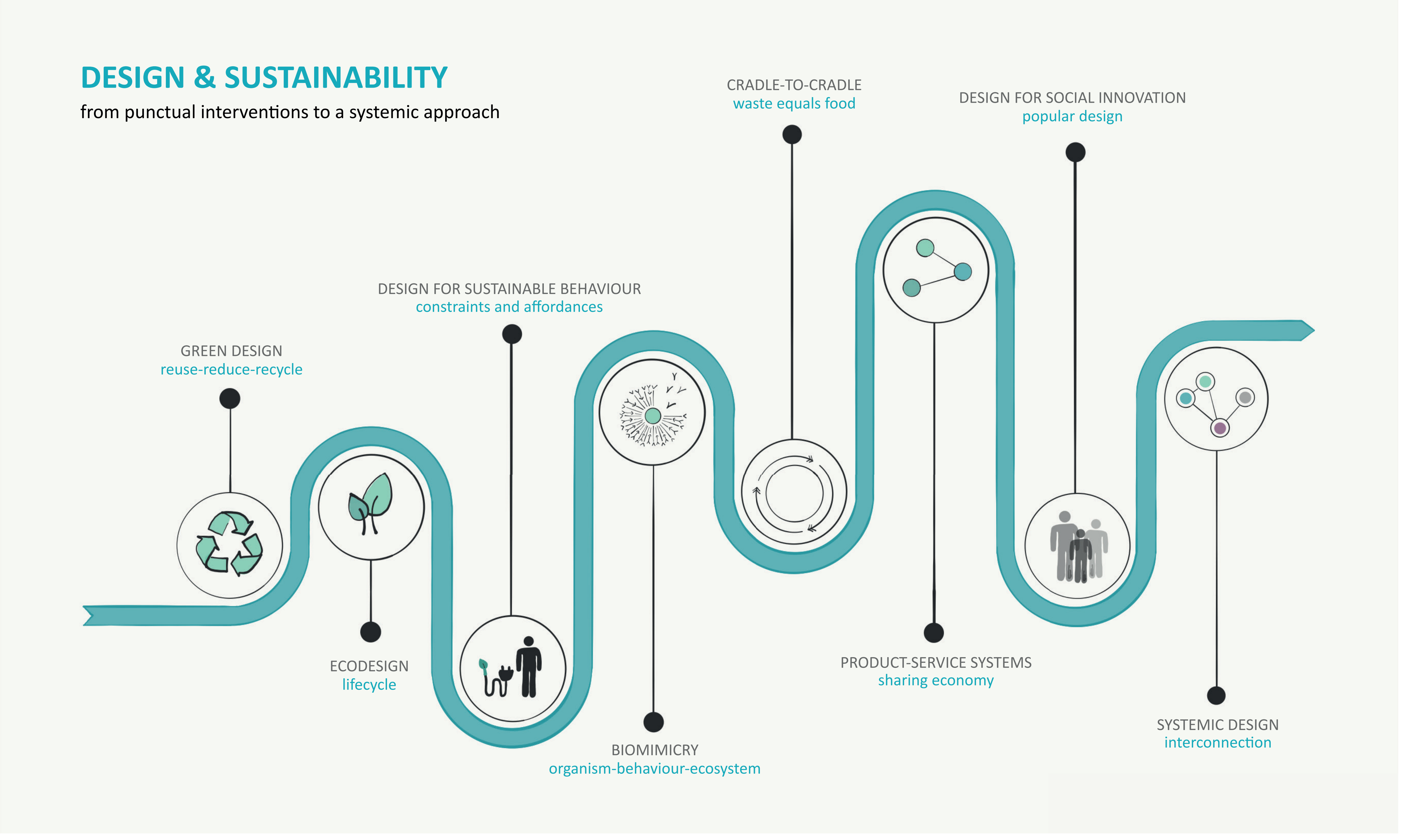
From cradle-to-cradle means to design each product following the principle according to which the waste doesn’t exist, and therefore the nutrients contained in the materials we use should be the element which shapes and defines the final design. Forms doesn’t have to follow just function but rather evolution, thus feeding the two distinct metabolic flows of technical and biological nutrients.



The original edition of this book – the American one – is the actual materialisation of the theories illustrated inside it. It is printed with an ink that can be retrieved and reused on plastic sheets that can be reused too, both within the technical metabolism, with the aim of making its physical content coherent with the intellectual one

1.2 Focus shift: from product to material

With the evolution of the idea of sustainability in the design culture, we witnessed a shift from punctual interventions on single products to a systemic approach, through which look at interconnections, and conceive each product as part of a system, node in a network of interactions (Myers, 2012; Antonelli, 2008).
Acting only on the social impact of design, as well as on products' life-cycle, proved to be ineffective in facing the complexity of today's global issues, as long as there is no intervention on the actual matter with which we design, and so on the nutrients flow among the open systems constituting our planet.
Such partial approaches are simply aimed at damage control, while the fundamental goal – in order to expand the equilibrium condition of natural ecosystems to human production systems – is to manage to give back the nutrients subtracted from the environmental system into a usable form. For this reason the attention of designers has shifted from design for sustainability to sustainable materials, so highlighting the centrality of the materials we use. Designers indeed have the opportunity to change processes behind products, and resources used to fabricate them, addressing the issue at greater length. To face environmental issues superficially, without fully understanding the effects of our choices, can be worse than doing nothing (McDonough & Braungart, 2002). A recycled material for instance, is not automatically "good" from the environmental point of view: recycling is often sub-cycling – just think of plastics, paper, and some metals – and it requires high impact chemical processes, as well as the employment of harmful contaminants. Therefore designers started to research bio-based materials as an alternative to fossil-based ones, drawing the attention on biopolymers.
Biopolymers or bioplastics, are materials derived from renewable biological sources such as plants, bacteria and algae. Unlike traditional plastics, they can be degraded by microorganisms present in the soil without any release of pollutants. These materials are not something new, but no-one gave them much attention since oil and its derivatives were cheaper and easily available. Only during the 1970s, with the oil crisis, people started to deepen the research on alternatives sources for polymer production. The first bioplastic was the Parkesine, trade name for the first plastic made from cellulose, created in 1862 by the British chemist Alexander Parkes. In 1897 in Germany the Galalite was invented, a material made from caseine, the milk protein, and treated with formaldehyde. In 1912 Cellophane was invented and patented, a transparent sheet made from cellulose and treated with chemicals and plasticisers to make it waterproof. In 1926, from his work with the bacterium Bacillus megaterium, the French researcher Maurice Lemoigne discovered polyhydroxybutyrate (PHB) the first bioplastic made by bacteria. Even Henry Ford experimented with bio-based materials, and in 1941 realised the "soybean car", made of tubular steel and panels of a composite material made from soybeans, hemp, flax and ramie. However, the outbreak of World War II suspended all automobiles production, including the soybean car experiment. Between 1950s and 1960s experiments on bacterial biopolymers were revived for the production on the industrial scale of Polyhydroxyalkanoates (PHA) and PHB. In the 1980s, after the oil crisis of the previous decade, the first bioplastic companies were set up, and in the 1990s the first biopolymers from plant sources were developed, extracting starches from agricultural crops, as in the case of polylactic acid or PLA.
For several years therefore, organic raw matter has been employed as new resource, tough often manufactured with chemical processes and additives which turned it into something different. Contamination and nutrients' waste however, is an even greater problem than the amount of waste produced. Mixing together "technical" and organic materials means that none of them could be retrieved at the products' end of life, giving rise to the so called "monstrous hybrids" (McDonough & Braungart, 2002). In this way we keep on consuming the available resources in a linear way, according to the take-make-discard paradigm. On the contrary, the natural world operates through circular loops based on the equivalence waste equals food (McDonough & Braungart, 2002), using rather than consuming the resources available.
The impact of the overall material life-cycle has to be properly taken into consideration. Bioplastics production for example, often resulted in greater amounts of pollutants, due to the fertilisers and pesticides used for crops and the chemical processing required for their transformation. Hence in recent years, designers started to look at new sources for the production of biopolymers, replacing plants with algae: abundant, available worldwide, fast-growing, requiring way much less land and water than terrestrial plants.



3. Evolution of the relationship between design and sustainability: from punctual interventions to an holistic and systemic approach wich takes into account social issues too besides technological and environmental ones

1.3 New Paradigms: re-thinking the system

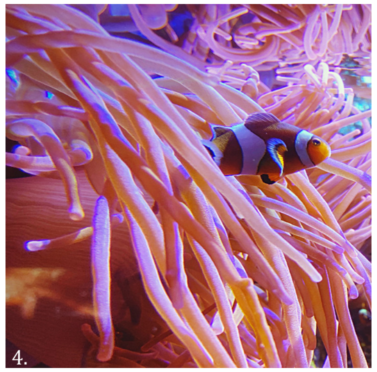
The many approaches described in the previous chapters, have as common point the tendency to isolate one of the many aspects of the same issue, facing them as something separate from each other – technical aspects related to environmental impact, social aspects related to consumption behaviours, procedural aspects related to production systems. This is no longer enough, and we need to introduce structural changes in our production and consumption systems, abandoning end-of-pipe and damage limitation solutions in favour of a systemic and holistic approach.

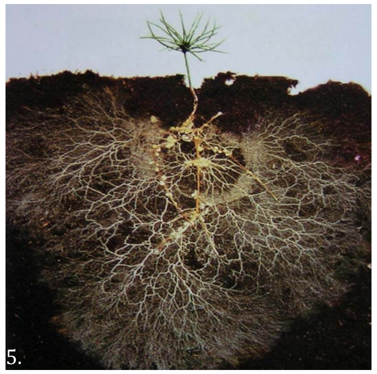
Usually, any kind of material innovation makes its way in our human-made world according to two stages: in the first place it spreads through imitation of materials currently in use, modifying the existing system as little as possible; subsequently instead, the whole system is redefined in the light of the aforesaid innovation (Manzini, 1986). That's what is happening with bio-based and living materials, which today are paving the way for a whole industrial revolution. Designers are returning to nature to source materials, not as throwback to a non-technological era, but recoding and decoding their structures to push their properties toward augmented applications and aesthetics (Lipps, 2019).

The majority of industrial materials and methods are damaging, although unintentionally. The linear and global industrial system exerts an "intergenerational remote tyranny" on future generations, through the effects of actions we implement today; and operating within the same exact system which is cause of the problem, according to the eco-efficiency concept, is limited to just slow it down (McDonough & Braungart, 2002). Damage control, as for example turning factories fumes wither or labelling a material as "more sustainable", can be extremely dangerous since it makes the negative consequences less visible and then more acceptable. As stated in a famous Einstein's quote we need a brand new way of thinking in order to solve problems caused by the old way of thinking.

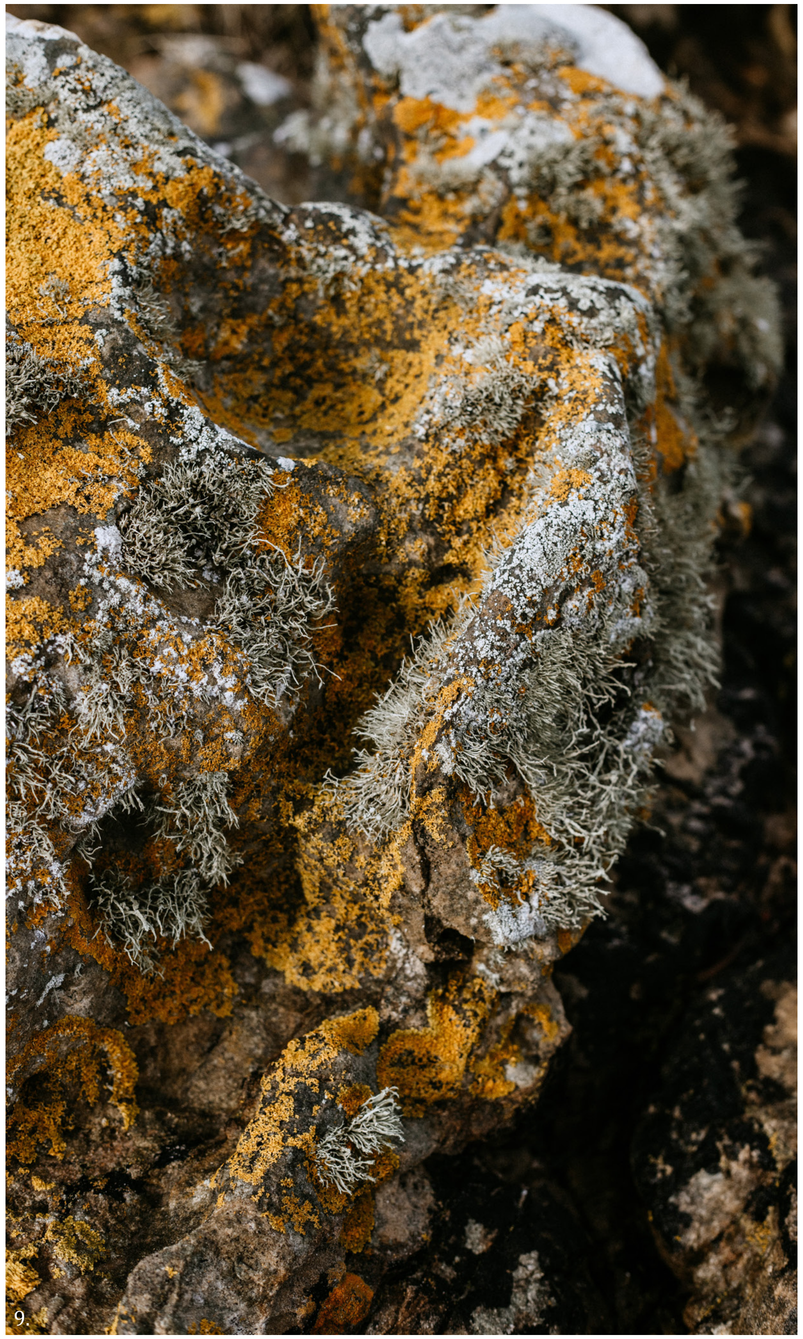
Symbiosis with Earth as our habitat is what allowed humanity to evolve. In biology Symbiosis is defined as a close relationship between two species in which at least one species benefits. There are different kind of symbiosis: Mutualism is a symbiotic relationship in which both species benefit; Commensalism is a relationship in which one species benefits while the other species is not affected; and Parasitism is a kind of symbiosis in which one species (the parasite) benefits while the other species (the host) is harmed.

Currently our relationship with the planet is a parasitic one, and shifting to a mutualistic symbiosis entails a radical change of perspective, impossible to achieve through incremental changes. For long time humans have embraced the dog-eat-dog culture, according to which only the strongest, the biggest, the most efficient and even the meanest survive, a culture based on the idea of competition and dominion. In nature however the one who survives and thrive, is who is able to adapt rather that who prevails over the other. Adaptation entails a relationship of interdependence between living beings, energy and materials of the place they inhabit (McDonough & Braungart, 2002). Interdependence, opposed to independence, is a systemic concept result of the permeability between open systems and the environment (Minati, 1998). In order to pursue a new mutualistic relationship between we humans and the planet, we have to learn how to operate within the context in harmony with it, and not despite nor against it.





4. Mutualistic symbiosis between anemone and clownfish: the anemone provides protection and shelter while the clownfish provides nutrients with his own waste and keeps away potential predators.
5. Mycorrhiza is a mutualistic symbiosis between fungae and the root system of plants, where fungal mycelium helps absorbing water and nutrients fostering plants growth, and the plant provides easy access to food for the fungus.
6. The symbiosis between the Cattle Egret and livestock animals is an example of Commensalism: the egrets forages following grazing cattle and feeding on the insects stirred by their movement, without affecting the cattle.
7. Rafflesiaceae are a flowering plant family known for being strictly parasitic upon the roots or stems of other plants. *Rafflesia arnoldii* in particular is the world largest individual flower, and it smells like rotting flesh to attract insects. Its lack of leaves doesn't allow it to photosynthetise making it an obligate parasite which steals nutrients from surrounding plants.
8. Ticks are an example of parasite which lives by feeding on the blood of mammals, birds, and other animals.
9-10. Lichens are organisms resulting from a mutualistic symbiosis between fungi and photosynthetic organisms such as algae or cyanobacteria. Both species can survive separately, but they often associate because of the benefits brought by this relationship: the photosynthetic organism provides the fungus with a constant food supply in the form of organic compounds, in return the fungus acts protecting the algae from the environment, provides anchor and helps collecting moisture and nutrients.



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CHAPTER 2

FUTURE MATERIALITY

ABSTRACT

The relationship between materials and design has been evolving and transforming over time. In the beginning, it was grounded on experiential knowledge and hands-on approach, but at some point it turned away from materiality establishing a dichotomy between hand and mind. Such relationship then, as a consequence of the multiplication of materials available which established a condition of hyper-choice, moved to the realm of analytical knowledge, untying the product from the material constituting it, and conferring it an abstract dimension. This gave birth to material libraries as fundamental tool for material knowledge, however, the analytical knowledge provided proved to be insufficient in order to adequately give back all tangible and intangible aspects of materials.

With the post-digital era we witnessed a return to matter, tactility and physicality, without neglecting the positive legacy of design thinking, which expanded the design range from products to processes and systems, characterising design as a way to determine the kind of relationship we establish with the surrounding world. Materials become now input of the design process, not anymore given entities to select from a list in the final stages of the project. The experiential knowledge becomes then a "transformational knowledge", which allows to overcome the gap between theory and practice, and deepen the relationship between material, product and process.

The more the comprehension of the surrounding world grows, the more the solutions of the artificial world get closer to the ones of the natural world. When biofabrication trespassed the the biomedical field and started colonising our material world, it paved the way for a new material and industrial revolution. Design went from learning from nature – with biomimicry and bionics – to collaborate with nature, dissolving the boundary which for long time separated Nature and Artifice.

Looking at the future of materials, we can observe two main tendencies very often intertwined one another: the reconsideration of waste as valuable raw material, and the collaboration with microorganisms in order to grow matter that can be harvested, or used as living system as a whole. The most distinguishing feature of such circular, abundant and biofabricated future materials, is that they are not eternal, flawless nor unchanging but alive: they are born, grow and die as any other organism on the planet.

2.1. Materials and Design

The Design Process has always been the result of the interaction between ideas and matter (Manizni, 1991), intentions and choices of designers, and the functioning of the systems they are part of. Schön[1], defines Design as a "reflective conversation with the materials of a situation" (1992). Any artifact produced by humankind then, can be seen as the materialisation of what Manzini defines "thinkable-possible" (1986), intersection between what can be imagined – and it's so related to the cultural sphere – and what is made possible by the techno-scientific development.

Design has always been a discipline based on a hands-on approach, nonetheless at some point it has turned away from materiality, creating a separation between mind and hand. The digital revolution and the consequent informatisation process that hit our society in the last century, was indeed accompanied by the idea of dematerialisation of the outside world, reduced to surfaces that convey messages. In practice, however, despite the forecast of a virtual immaterial world, our reality is characterised by an increasingly hulking and constantly expanding materiality, which rapidly turns into piles of waste (Maldonado, 2003). At the same time, we are immersed within the material world and also part of it. We live in a multi-sensory reality, made of things that we can touch, smell, see, hear and taste. Materials represent the building blocks of such reality, basic elements each equipped with a specific set of sensory attributes that interact with light, air and people around it (Schifferstein & Wastiels, 2014).

The post-digital era is so been characterised by a return to matter, to physicality of objects, tactility and craft, "returning design to his haptic origins" (Gerritzen & Lovink, 2019). What is left as positive legacy of such transition, is that with design thinking, design expands its range looking not only to products but also to processes and systems, becoming a "way to work, live and think" (Gerritzen & Lovink, 2019), a way to produce and consume, and a way to determine the kind of relationship we establish with the outside world.

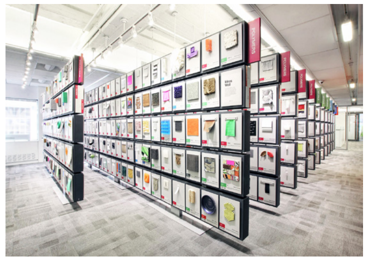
Through design we can explore materiality other than materials themselves, looking at materials for their social significance, as me-

1. Donald Schön was a philosopher and professor in urban planning at MIT who introduced the concept of reflective practice in 1983, distinguishing between two kinds of reflection: reflection in action (thinking while acting) and reflection on action (retrospective contemplation of the action).

aningful and implicated in social acts, able to deeply affect human thought and behaviour, enabling and empowering people's lives as well as constraining them (Tilley, 2007). Materials then, are not a blank slate or tabula rasa, available to to be freely and passively shaped, but they have a specific identity, an "hidden character" (Ashby, 2014), and act as collaborators (Rosner, 2012) in the design process, according to this "character". Over the years, materials have shifted from being given entities upstream of the project, to be themselves something to be designed, generating innovation and changing the way we think and produce objects (Doveil, 1991). The evolving relationship between materials and design, gave rise to a dynamic process of socio-technological innovation (Lucibello, 2018), where Science, Design Research and New Craft are blend together.

2.1.1. Hyper-selection and Material Libraries

Originally the designer was the one who knew materials and techniques, and materials were something to select from a preexisting palette. The knowledge of designers was then built through the experiential approach of learning-by-doing, not a passive education based on superficial factual knowledge, but an active elaboration of ideas, which locates in the experience the starting point for knowledge building (Dewey, 1938). The Bauhaus school was structured around this approach, placing the laboratories at the very core of the teaching activities, juxtaposing the study of materials and processes alongside the study of shape. Experimentation on materials for design its rooted in particular in the textile design laboratory by Annie Albers, and hers research on the organoleptic and expressive qualities of textiles, which represent the first attempt to build a new matter, beyond chemistry and controlled by the designer (Branzi, 2004).
Subsequently, the acceleration undergone by the techno-scientific innovation, resulted in the proliferation of new materials. Besides the "basic" materials such as wood, metal and plastic, the material world expanded into a universe made of many subcategories constantly and rapidly updating, developing new hybrid materials, and determining a condition of hyper-choice (Lucibello, 2009). The hyper-choice though, implies the arise of a knowledge gap with regard to materials, since the amount of information is so huge that is impossible to be adequately handled by designers. Abstract knowledge of materials then, became the only way, turning the design process into an activity that is mostly carried out sitting behind a computer or at a drawing table.
In an effort to shorten this knowledge gap, in 1997 G. Beylerian founds Material ConneXion in New York, the first material library, a physical and virtual place where materials' samples and information relating thereto are collected. In the following years, many other material libraries popped-up allover the world, becoming an essential tool for designers, acting as material archives as well as consultancy services. These databases connect the companies who produce and manufacture materials with designers who apply and use them. In this way, is possible to acquire lot of information with no need to reach each company individually, creating a network among different fields of production.



1. Material ConneXion's material library

The materials in the availability of the libraries are categorised following different criteria, involving technical and performance features as well as sensory and perceptual ones, but also ecological requirements. However, any categorisation is always incomplete, since with the multiplication of possibilities and materials is more and more difficult to divide them into rigid categories. One way or another categories overlap, material families no longer exist, and an objective and universally valid classification criterion is impossible to determine.
Material libraries have so become a quick and widespread means of communication of information about materials, helping designers in the acquisition of knowledge about the latest material innovations. Increased knowledge however, doesn't mean facilitating the selection of the right material for the project. It provides fundamental information which would otherwise be unreachable, but this is not enough to completely replace the experiential dimension. Compared with the past indeed, there is a loss of the ability to manage materials and processes, and to be their "inventor" or manufacturer (Lefteri, 2009). Above all, this tendency underlined a design approach where the project is something abstract, untied from the material it is made of, which, in turn, is something selected from a range of options because more appropriate, performative or economically viable. Data of designers though, come in form of senses (Lee, 2019?): we experience a multisensory reality where the overall perception is not a mere sum of each sensory stimulation, but is given by the interaction among them. In the attempt to translate the perception of a material into a list of characteristics – which becomes together with pictures the only form of interaction – we lose the overall view and miss the opportunity to grasp all the intangi-

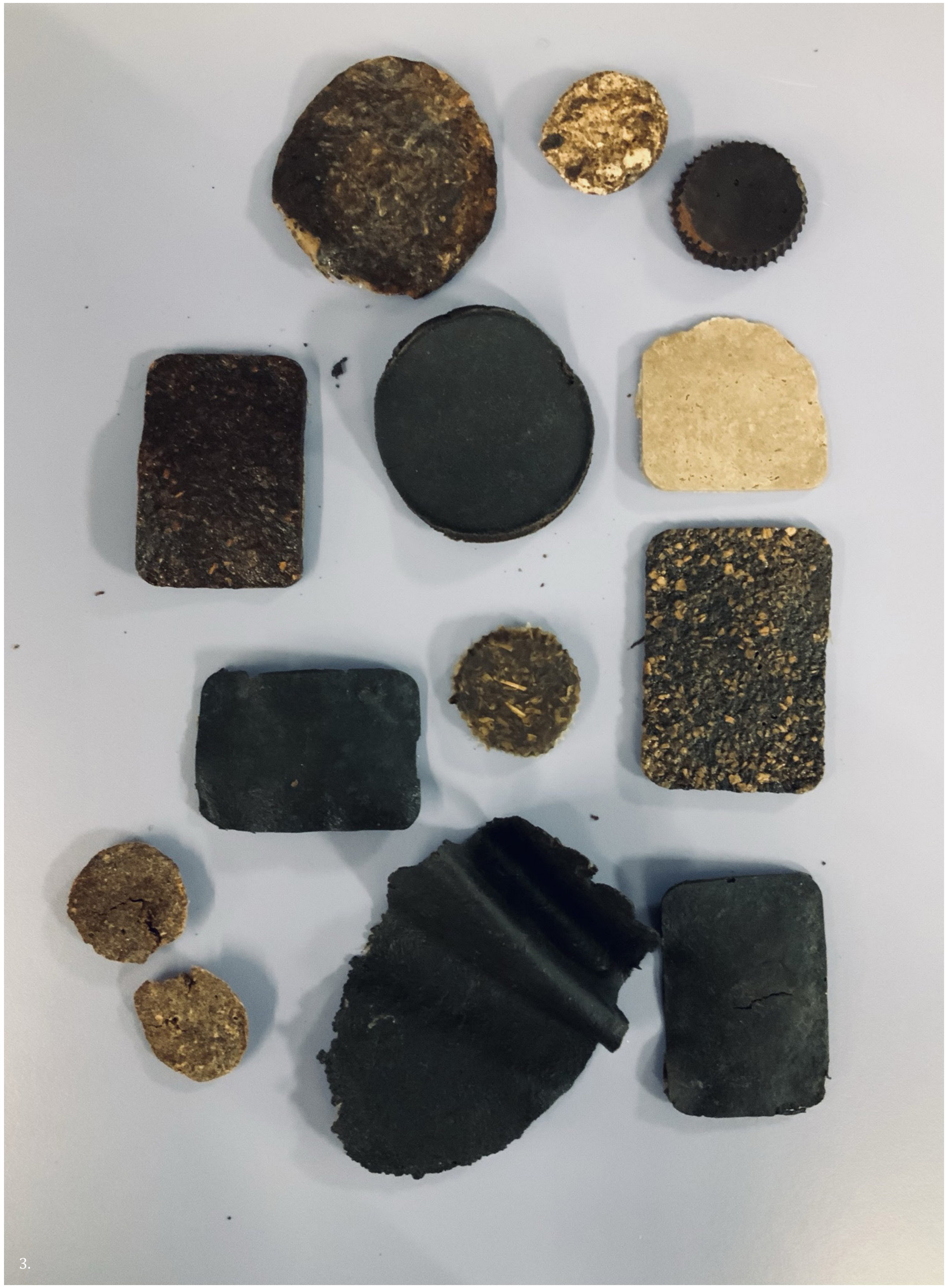

2.

2. Material tinkering
3. Do-it-yourself materials from olive oil production waste realised within the project "Bio-packaging made from agro-food industry waste", research team: Prof. C. Cecchini, Prof. S. Lucibello, C. Del Gesso, L. Trebbi

ble aspects related to meanings and emotions, which originate from sensory interaction.

2.1.2. Materials as input of invention

In the last few years are emerging new approaches to materials for design, both in teaching and in the design practice, with a shift from mere selection to direct experimentation (Trebbi, 2018). Materials become input of the creative process, with a transition from selecting materials for the project to designing with materials, overturning the traditional and linear design process based on problem solving – which starts from a need to transform it into a product (Lucibello & Trebbi, 2018). The experiential approach instead, starts from the observation of materials, their physical exploration, tinkering and manipulation, in order to kick-start the creative process and begin the experimentation. This allows to carry on a sensory and perceptual investigation, through which integrating the technical-productive features together with the aesthetic-perceptual ones, vehicle of sensory and immaterial aspects which significantly contribute to the overall quality of the product. The centrality of the material as design input is the basis of the Design with Materials approach (Lucibello, 2018), as well as of the Material Driven Design approach (Karana, et al., 2015), which considers the material not only for what it is, but also for what it does, what expresses, what elicits to us, and what makes us do, thus designing in the light of the so called Material Experience (Karana, et al., 2014).
The involvement and interaction with the material plays a significant role in the cognitive process, and the manual activity represents a tool through which "logically thinking through senses" (Nimkurlat, 2010), understand and learn through experience, and deepen the relationship between material, shape and process through a practical investigation. Such cognitive process is what the psychologist Edward de Bono defines lateral thinking (1967): the perceptual part of thinking which allows us to organise the external world into pieces that we can then "process". The human brain indeed, works learning and then "locking" subconscious behaviour and thought patterns, in order to let the conscious brain focus on something else. This can result into getting stuck between certain boundaries or perspectives that we can bypass through creativity, looking at the same issue from a different and unusual angle.
The experiential knowledge of the material then, allows the desi-

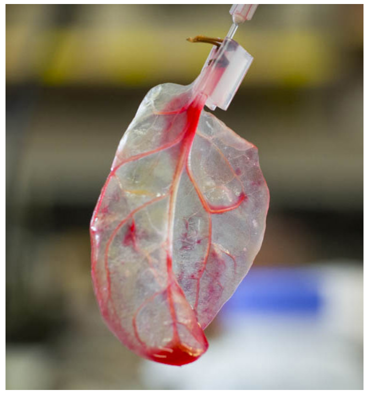

3.

4. Up series, Gaetano Pesce

gner to overcome the gap between theory and practice, understand and interact with production processes, experiment with perceptual features, imagine new applications and suggest new rules. Through the material exploration, opposed to analytical knowledge, can arise invention. An example is the "Up" seats family produced since 1969, developed by Gaetano Pesce exploiting the distinctive features of polyurethane. The inspiration arose right through the observation of the qualities of a shower sponge that, like the polyurethane seats packed in vacuum bags, could be compressed and then return to its original volume when released (Martin, 2017).
Starting from the material exploration and the design with materials, the experiential approach goes up to the design of materials themselves (Lucibello, 2018), with DIY (Do It Yourself) and self-production practices implemented by designers. Such practices highlight the importance of the contribution provided by emotions – generated within the material's creation process – in inspiring the design process, unlike what happens when the material is selected from a pre-existing palette (Rognoli, Ayala Garcia & Parisi, 2016).
The experiential approach let designers investigate through practice, gaining a transformational knowledge rather than a merely documentational one (Ingold, 2013; Groth et al., 2019). Design then, does not simply intervene in the final stages of the project, but can step in from the very early stages and act on processes, resource management, lifecycle, as well as on the semantic and emotional side of products.

2.2. A Material Revolution

Today, with biofabrication, we are witnessing a new material revolution which is paving the way for the next industrial revolution. The matter we relate to as designers becomes alive, marking a radical turning point for the objects populating our world as well as the way we produce and consume them.
Biofabrication – literally fabricating with biology – is a technology that found application in the first place in the field of regenerative medicine and tissue engineering with the goal of growing replacement parts for the human body. It is usually defined as the production of complex biologic products from raw materials such as living cells, matrices, biomaterials, and molecules. In the first place, it started as bioassembly, automated assembly of cells containing building blocks. Thereafter, this rapidly evolving technology has been influenced by the development of 3D printing technologies, giving rise to bioprinting, which allows direct cell deposition in organotypic architecture. Examples of application in the biomedical field, are the fabrication of microcardial tissue through alginate extrusion-based bioprinting, as well as skin biofabrication through jetting-based bioprinting of collagen (Seol et al., 2014).
Another important application in the biomedical field is tissue engineering from plants. Andrew Pelling from University of Ottawa, has grown human ears from apples: through removing plant cells from leaves, is possible to obtain a cellulose structure which acts as a scaffold for the growth of human cells, creating apple slices shaped as human ears. Following the same process, a multidisciplinary research team from Worcester Polytechnic Institute, used spinach leaves to rebuild heart muscle tissue, with the leaf branches acting as blood vessels.
Biofabrication is today expanding and evolving, giving rise to new researches involving different fields and disciplines, from synthetic biology to food sciences, from fashion to product design. The tissue engineering techniques of regenerative medicine have indeed found new applications. One of the most disruptive examples is the production of lab-grown cultured meat, obtained harvesting



5. Heart Tissue on Spinach Leaves, Worchester Polytechnic Institute

6. Cultured meat by the Dutch company of food technology Mosa Meat

7. Zoa cultured leather by Modern Meadow

muscle cells from living animals and multiplying them in order to create tissues. In this way, besides the relevant ethical aspects, is possible to drastically reduce the space used, emissions and environmental impact of industrial livestock farming, which is today responsible for 7.1 Gigatonnes of CO_2-equiv per year, representing 14.5 percent of all anthropogenic GHG emissions (FAO, 2013). In 2015, the design researcher Amy Congdon, with her speculative project "Biological Atelier" showed how tissue engineering could be used to grow biological textiles for the fashion industry, using textiles as a scaffold for cell growth. Not long thereafter, in 2017, Modern Meadow – a US company led by the British fashion designer Suzanne Lee – launched Zoa, the first ever lab-grown leather. Yeasts are genetically engineered to produce collagen instead of alcohol during fermentation. In this way, the team harnesses living organisms to manufacture new materials, which, freed from the animal form, can assume any shape or thickness. Biofabrication then, has today transcended the boundaries of the biomedical field, and is seeping into the world of materials with the potential of affecting many aspects of our everyday life, marking the birth of Biodesign.

2.3. Artificial Nature, Natural Artifice

The relationship between Science, Nature and Design is an ancient phenomenon constantly evolving, rooted way back in the past as of the Vitruvian search for harmony. The more the comprehension of the surrounding world grows, thanks to advances in science, the more the solutions of the artificial world get closer to the ones of the natural world. Talking about the techno-scientific evolution of humanity, which is reflected in the materials we use, Ezio Manzini pinpoints three main stages (1986): suffered complexity materials, such as the first materials used, like stone, wood and the first metals; controlled complexity materials, made available through the development of processes able to produce homogeneous and isotropic materials equipped with specific properties; and finally managed complexity materials, where the manipulation goes deep into the structure of matter, and anisotropies and impurities can be produced in order to get specific performances. Looking at the evolution of materials, as well as at the relationship between humans and matter, we can see a tendency to develop and imagine increasingly complex materials, characterised by behaviours more than performances, and by an high amount of data, so materials increasingly similar to biological organisms (Langella, 2003).
The boundary which for long time separated Nature and Artifice, is actually a cultural construct. This boundary today is dissolving with the growing awareness that we are nature. It is no longer "humans versus nature", but "humanity as integral part of nature with each mutually affecting the other" (Mc Quaid, 2019).
Going back in time, we can find this concept since ancient Greek philosophy with Plotinus, which stated that "all is One", and the universe in its countless multiplicities carries always in itself the whole.
Therefore today, we have to make an effort to always recognise "the whole in the part" (Minati, 1998). It is indeed impossible to still look at humans as something outside of nature, when the 95% of birds and mammals on the planet are humans or livestock exploited to feed or clothe them; half of the world's habitable land is used for agriculture, the 77% of which is used for livestock and only the 23%

2. Microplastics are everywhere, in the sea, on glaciers and even in human feces. Recently, they have been found even in the human placenta. Moreover, it has been found that plastic micro particles can travel even through air and be transported across the globe. Recent studies have reported the finding of microplastics on Pyrenees, notoriously wild and uncontaminated areas. The particles were transported there through atmospheric phenomena and could have been traveled for 100 km.

8. Plastiglomerate by Patricia Corcoran, Charles J. Moore and Kelly Jazvac, 2013: melted plastic waste conglomerate mixed to hearth sediments and organic debris, collected in Hawaiian coastline

for crops; and microplastics are invading waters worldwide reaching even the most remote places[2] (Ritchie & Roser, 2018). Agriculture itself is one of the first form of design of nature. The work of the artist Sam Van Aken "Tree of 40 fruit", realised using grafting techniques to combine different fruit trees, represent a form of "augmented nature" (Lipps, 2019) where we can no longer distinguish between natural and artificial.

The world we inhabit must be seen as a whole, or rather as a complex system that can acquire features which don't belong to its individual parts, but emerge from the interaction between them. This novel perspective is affecting many fields of knowledge, and is based on the core concepts of evolution and complexity (Langella, 2003). It has is background in the scientific thought of the twentieth century, starting from the work of the biologist Ludwig von Bertalanffy, father of the Systems theory (1937), which undermined the basis of sure and certain science, opening the doors to the topic of complexity. In 1963, with his Chaos theory, the mathematician Edward Lorenz identifies in chaos the status of dynamic systems, a new kind of order characterised by unpredictability, but that can still be determined. All is then in relation with everything, and the modification of a single factor can bring unpredictable transformations to any other element.

2.3.1.Learning from Nature

The natural world has gone through 3.8 billion years of research and development, with failures and successes, in the search for the most effective and convenient solutions. Looking at nature as source of knowledge and inspiration, is an ancient phenomenon. In the beginning it assumed a decorative, symbolic and semantic function, as happened with Art Nuveau between the nineteenth and twentieth century. In the late 1950s the term "Bionics" was coined to describe the research of formal and geometric principles of nature for their technological transfer to human-made systems. In the following decades, Biomimicry has pushed further this relationship between nature and the human-made world, looking at nature not only as morphological reference, but as a source of new methodologies and logical principles (Langella, 2003), seeking "the logic of formation rather that the description of forms" (Legg, 2017).

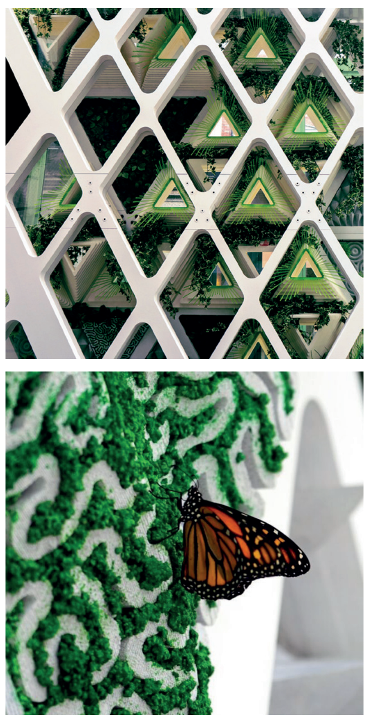
In 1997, Janine Benyus has deepened and disseminated this concept in her book "Biomimicry: Innovation Inspired by Nature". Nature becomes a model, source of inspiration for designs and processes; a measure, ecological standard and evaluation criterion; and a mentor, something we can learn from. Following these principles we can act at three different levels: on products, processes, and finally systems. The 3D-printing technology represents an example of biomimicry. Nature indeed, creates biological structures trough additive "manufacturing", as in the case of spider webs or silkworm's cocoons. The same goes for auxetic materials which, since having a negative Poisson ratio, expand perpendicular to the solicitation when subjected to traction, getting thicker instead of thinner. This property can be found in tendons, cat skins, muscle shells and so on, and enables high energy absorption as well as fracture resistance.

The project Water Reaction by Chao Chen, starts from the study of pine cones and their ability to open and close reacting with water. This property has been transferred to an architectural laminated skin which stays open in good weather conditions, letting air and light flow inside, and closes when in contact with water, preventing the rain to penetrate. The same principle has been implemented in HygroSkin Meteorosensitive Pavilion, by Achim Menges, Oliver David Krieg and Steffen Reichert, a climate-responsive architectural skin which opens and closes autonomously in response to weather changes.

Another example is the structural colouration found in butterflies' wings, peacock's feathers, bugs' exoskeleton and also flavobacteria. This kind of colour isn't determined by pigments but by the microstructure of the surface which reflects light according to different angles, often resulting into iridescence. The fashion and textile designer Donna Sgrò realised in 2009 the first structurally coloured dress using Morphotex fibers, which mimic the colour of Morpho butterflies. Techno Naturology by Elaine Ng Yan Ling is a project which explores the potential of natural sensing system like wood combined with shape memory alloy and polymers. Her collection includes responsive textiles and architectural surfaces which react to different external stimuli such as temperature, moisture or movement. Cillia, by the Tangible Media Group of MIT Media Labs, is a 3D-printed micro-structure which mimics hair at different resolutions. In nature hair has many functions – from the more technical as insulation, adhesion or locomotion, to the more perceptual such as sensing, tactility and aesthetic – which can now be transferred to 3D-printed artefacts. With biomimicry designers work to decode nature's principles and laws. With the growing understanding they are moving from imitating to stimulating nature(Lipps, 2019), as in Alexandra Daisy

9. Water Reaction by Chao Chen

10. Totomoxtle by Fernando Laposse



11. Monarch Sanctuary by Terraform ONE

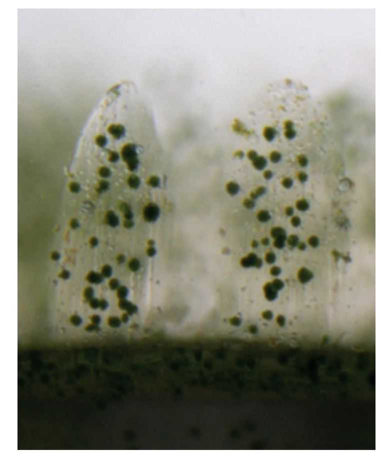
Ginsberg's Resurrecting the Sublime. With this project the designer recreates the smell of extinct flowers using biotechnologies and working with stored DNA specimen, in order to learn which smell molecules the flowers may have produced when alive.

2.3.2.Collaborating with Nature

In the last decade biodesign went beyond imitation of nature interacting with her as a co-worker (Collet, 2017), designing together with nature and often designing nature herself. Today, in the Antropocene era, everything is designed, but on the flip side everything can be re-designed (Ryan, 2014). The human footprint on the planet has deeply upset the balances among ecosystems. Now we have the potential of building new ones, regenerating and remediating through what Paola Antonelli defines "restorative design", as highlighted by the XXII Milan Triennale "Broken Nature" (2019).
Restorative design can act to reconstruct biodiversity, as with the Totomoxtle project by the Mexican designer Fernando Laposse. Using the colourful native corn husks to realise a new veneer material, he pushes for the preservation of local crops, and the craft traditions related. Biodiversity preservation means also to design for other species. An example is the Monarch Sanctuary by Terraform ONE, the concept for a new commercial building in New York City. The aim is to establish a coexistence between humans, plants and butterflies, integrating monarch habitats in different parts of the building, making it a large-scale Lepidoptera terrarium. In this way it will be possible to provide an habitat for wild monarchs and increase their population through colonies, at the same time raising awareness about the decline in their population and biodiversity loss. Similarly, Bioreceptive Concrete Panels by Beckett, Cruz and Ruiz, want to encourage the growth and thrive of life, creating the enabling conditions for nature to spread. This concrete panels are designed to accomodate and support mosses, lichens and algae, organisms which absorb air pollution through photosynthesis.
Interacting symbiotically with other species, microorganisms and life forms, can result in mutual benefits such as climate control or lowering of emissions and energy used to heat and cool buildings. Another example of designing with and for life, is the bioprinting of coral structures which, mimicking the optical properties of corals, are able to grow micro-algae, reproducing the symbiotic relationship they have in the oceans. This project is the result of a collaboration between Cambridge University and University of California San Diego, and uses printed corals as incubators for algae cells, which can in this way grow at much higher rates if compared to standard growing mediums.

Design is one of the human activities more loaded with consequences, shaping behaviours that affect any aspect of life (Antonelli, 2019). Starting as an activity in service of market, it moved gradually to a human-centred approach, in the pursue of the progress of society rather than technology.
However, human-centred or user-centred design reflects a totally anthropocentric perspective which today appears obsolete. If it is able to shift from an egocentric to an allocentric mindset, moving humans from the center to the edges (Caffo, 2017), design can become a repair tool instead of a tool for destruction.
We need to implement interspecies collaborations, connect and empathise; shifting our attention from short-term individual interests, to a collective, systemic and long-term approach (Wilson, 1999). This of course doesn't mean that design is the ultimate panacea, the solution to every problem. Means instead that we can reframe our priorities and choose the the future we want for ourselves and the planet (Mc Quaid, 2019). We should ask ourselves which idea of "better future" are we chasing, and whom would benefit from it. If we learn to look wider, long-range and long-term, we can easily understand that what is better for humans is what is better for other species and nature as a whole. In order to establish an equilibrium condition between the many terrestrial ecosystems, we have to design for an harmonious development, substituting the linear concept of growth with the concept of evolution. Within the system theory, the concept of harmonious development is related to harmony among all growth process, assuming as necessary condition that none of them has constantly zero nor negative value (Minati, 1998).
In this blend between biosphere and technospere, materials, resources, processes and technologies that we are facing belong to the natural world, and are subject to its laws. The matter of the project becomes alive, and as designers we have to learn to interact with it in a new unprecedented way.

12. Bioreceptive Concrete panels by Marcos Cruz, Richard Beckett and Javier Ruiz



13. Microalgae growing on 3D-printed coral structures, University of California San Diego and Cambridge University

Systemics, Complexity and Transdisciplinarity

Towards a new approach to knowledge and research

With the term systemics we refer to the transdisciplinary study investigating the principles of organisation of complex entities and phenomena.
System Theory was born in response to the new knowledge acquired in the biology field in the beginning of the twentieth century, marking the birth of the organicist thought opposed to the mechanist one of the nineteenth century. It was developed for the first time in 1940s by the Austrian biologist Ludwig von Bertalanffy, whose researches brought significant contributions to cellular and comparative physiology as well as cancer research, but who is mostly known as father of the system theory.

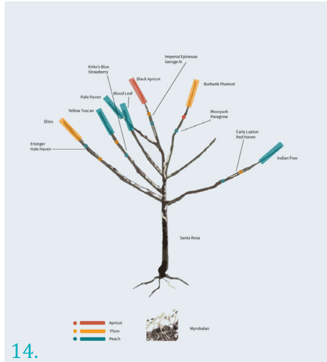
Bertalanffy's approach was a reaction against reductionism in the attempt to revive the unity of science. System theory indeed, conceives the world not as a chaotic complex of elements characterised by linear causality, but as an organism equipped with principles and laws involving the totality of its constitutive components.
It represented then an alternative to the classical rationalistic approach, according to which single elements are studied individually and later added to one another, on the basis of the assumption that relational behaviour has a linear nature.
System Theory focuses on the relations between the parts which make them into a whole instead of reducing entities and phenomena to the properties of its constitutive elements. A system can therefore be defined as an object which, despite consisting of different parts, acts as a whole. Its constituent parts indeed, are mutually interconnected and interacting one another or with the environment, so that the behaviour of each part is determined by the relationships in which it is involved.
Systems are structured hierarchically, consisting of multiple levels: the higher level provides an abstract overall view of the whole, while the lower level reveals a multitude of interacting parts. This hierarchical nature entails different levels of complexity and the fact that on the higher levels there are properties which aren't visible at lower levels, called emergent properties. The system's elements indeed, confer to the overall system properties which aren't the mere sum of the element's properties but are totally original, emerging from their interaction.
Moreover, unlike what happens within the scientific field where phenomena are analysed through

Ludwig von Bertalanffy started his academic career in Austria in 1938 as director of the Biology Institute of the University of Vienna, where shortly afterwards he joined an internationally famous group of scientists and philosophers known as Vienna Circle. Later he moved to Canada, at the University of Ottawa, and then to the United States at the University of Buffalo, New York

Edgar Morin is a French Philosopher and Sociologist known as a founder of transdisciplinarity, he dedicated his work to the problems related to a "thought reform", highlighting the need for a knowledge able to overcome the current subdivision and educate to complex thought

closed system models, as in physics for instance, in the real world systems are open and interact with their environments. Any organism is nothing but an open system constantly exchanging matter and energy with the environment, therefore interacting with other systems outside of itself.
It follows that in the totality of each system, a single element has to be examined in relation to its context, looking at the interconnection with the other elements and the behaviour of the whole system in order to acquire an actual knowledge around it. Conversely, any modification introduced into an element will be reflected both on the behaviour of the other elements and on the overall behaviour of the system.

With system theory we shifted from the metaphor of the machine to the metaphor of the organism, and therefore from complication to complexity, in order to interpret the world we inhabit. The concept of system becomes then a key notion for the formulation of a new scientific conception of the world, making possible to face complex phenomena, for whose study the determinist linear approach has revealed to be insufficient.
Edgar Morin, one of the major players in the revolution of complex thought, tells us that a complex phenomena cannot be understood disassembling it into its constituent parts, but we need to grasp the interaction among them and the overall view connecting the parts to the whole (Cipro, 2015). A complex object indeed, is made essentially by interrelations, interactions, interferences, complementarity and opposition between constituent elements (Morin, 1973).
Such vision leads to reevaluate the subdivision of knowledge into disciplines as well as hyper-specialisation which reflect the mechanist approach, and pushes research towards a transdisciplinary dimension cancelling disciplinary boundaries. Furthermore, it has also implications in the ethical field, pushing researchers to broaden the range of their responsibilities far beyond their specific sector (Cipro, 2015).
Collaboration and contamination among disciplines, and in particular between science and design as happens in the field of biofabrication, allows the hybridisation between the analytical approach of science – which develops vertically – and the synthetic approach of design, the "comprehensive synthesist" (Papanek, 1971), which develops horizontally and is by its nature transversal to the many compartments into which we are used to subdivide knowledge.



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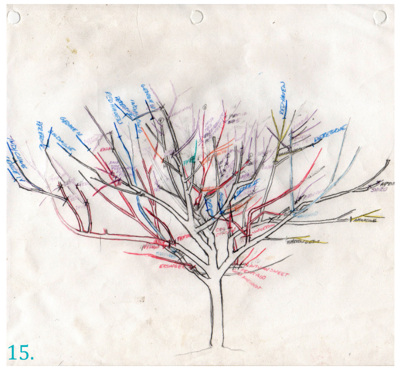


15.

14-15-16. Tree of 40 fruits by Sam van Aken

16.

2.4. Born, Grow, Die, Reborn

Despite the numerous theories which have been highlighting the interconnection between ecology and design for many years now, within the design practice such issues have been neglected for long, remaining good intentions never applied and well away from reality. Therefore decades of environmental crisis have followed, that led to new awareness – starting with the concept of limit and development in a limited world – and gave rise to countless novel environmental issues to face. It is the case of plastics and micro plastic pollution, fossil-based disposable products, planned obsolescence and electronic waste, synthetic dyes and the release of harmful chemicals in the environment as well as on our body, just to mention some. This gave birth to a new chapter of design history, as well as to a new generation of designers who is reinventing its practice with disruptive and radical approaches and who, through the focus on materials and processes and the embrace of the “different states of temporality” of materials (Agapakis et al., 2020), is paving the way for a future characterised by alternative systems of production-consumption.
Once discarded the idea that the world is a mine at our disposal from which freely extract resources to the bitter end, we can turn our gaze elsewhere, towards new materials and resources in the pursue of an “alternative abundance” (Franklin & Till, 2019): looking at waste from current production processes as valuable resource, exploring new kinds of farming with algae cultivation, and acting collaborations with microorganisms to grow organic materials and dyes. The principle is to understand and adapt to the functioning of the natural world we are part of and therefore implement circular and cyclical processes in order to establish symbiotic relationships between social and environmental systems. Eliminating the idea of waste according to nature’s law “waste equals food” (Braungart & McDonough, 2002), means to ensure that materials at the end of their lifecycle do not represent anymore something troubling which has to be disposed of, but they can instead be directly returned to the ecosystem as new resource. The time dimension becomes then a predominant element and materials are designed according to

their life-cycle, taking into account the "internal clock" of matter (Langella, 2003). We need to understand the "time" of the planet ecosystem and adapt to its velocity and cycles duration. With biofabrication substances are transformed into new matter, which relatively rapidly transforms again into something else with biodegradation. Non-biodegradable materials however, die and transform anyway, but in way much longer timeframe and often releasing harmful pollutants into the environment.
Looking at the future of materials, we can thus observe two main tendencies very often intertwined with each other: the reconsideration of what was once waste as valuable raw material, and the collaboration with microorganisms in order to grow matter that can be harvested, or to be used as living system as a whole. The most disruptive feature is that such "future" materials are not eternal, flawless, static or unchanging but alive: they are born, grow and die as any other organism on the planet including us humans, in a continuous cycle that is repeated again and again.

2.4.1. Waste

Within the current industrial system there is a huge amount of waste generated through the various stages of each production process. Starting from agriculture, where usually only the most precious part of the plant is used while the rest becomes biomass which is fermented or chemically treated to produce fuels and electricity, burned to produce thermal energy, or used as food source for livestock farming. Also the following stages of food processing produce many kinds of organic waste such as peels, shells, fibres or wastewater.
The designer Tamara Orjola, with her project "Forest Pine Wool", researched the potential use of waste from wood processing. Usually indeed in the wood industry billions of pine needles go unused, while with different manufacturing techniques such as crushing, soaking, steaming, carding, binding and pressing, they can be transformed into paper and textiles, extracting at the same time essential oils and dyes. "Cornspan" is a material developed by Apilada Vorachart starting from his researches on the atmospheric haze effect in Chiang Mai province, Thailand, caused by the burning of agricultural corn husks and cobs after the harvest. The designer uses corn husk fibres to manufacture panels for sound and thermal insulation that can be used in local construction. Also waste from the zootechnical sector can be turned into a valuable material: Merdacotta by Locatelli and Cipelletti is a material made from cow dung, processed to create a clay composite used to produce tiles, pots and tableware, giving new life to a material amongst the poorest.
The manufacturing industry produces a wide range of waste streams besides organic waste, including offcuts of leather and textiles, glass and clay scraps, stone dust, etc. Sophie Rowley experimented with different kinds of common waste within her project "Material Illusions", turning them into objects and furniture with entirely new aesthetic. An example is the reuse of denim offcuts layered into rigid elements in a way that recalls the natural processes of earth stratification and erosion. With a similar process leather industry leftovers are used by Barbora Veselá to create a pattern based on rock formations on the surface of her "Geology of Shoes" footwear. Jorge Penadès instead, mixes together shredded leather and natural bone glue to create furniture with marble-like patterns.
Waste however, shouldn't be intended just as the leftovers resulting from industrial processes, but also as what we produce in the everyday life within the urban environment, both on the wide scale of the city and on the small scale of household waste. The "RE-source" research project, by Ester van de Wiel, Joost Adriaanse, David Hamers and Ginette Verstraete, maps out flows of residual urban materials in the city of Rotterdam, NL, in order to develop strategies that show how design interventions in public spaces can reframe residual materials into resources which can be used again and again. The same principle is at the base of the "REFLOW" project, focused on development of constructive metabolic processes for material flows to implement circular economy city models, involving different pilot cities in urban and peri-urban environments across Europe. The "Precious Plastic" project by Dave Hakkens is a combination of people, machines, platforms and knowledge aimed at creating an alternative global recycling system. Through collection points citizens and local businesses can gather plastic waste, which is then transformed into new products using different machines. The project is open-source and can be implemented everywhere through starter kits, in order to create a worldwide network to connect all the local realities in a global community. The centrality of people and the social side of environmental issues is at the core of "ReMade in Sanità", a project which combines technology, social innovation and ecology. Founded in Sanità district in the city of Naples, IT, defined a suburb in the hearth of the town, it want to offer an alternative waste management model through virtuous

17. Material Illusions by Sophie Rowley

small recycling plants able to turn urban plastic waste and metals derived from e-waste into new products, increasing at the same time people's sensitivity on such issues. Moving on a smaller scale, in 2011 Philips presented the "Microbial Home": a set of tools and furniture elements through which turning the home into a biological machine able to convert waste into power, provide lighting and preserve food in unconventional ways, creating a cyclical ecosystem comprising different domestic areas and activities.
A material with a great potential for new applications is human hair, abundant and renewable resource that has always been seen as waste. Studio Swine created "Hair Highway", a collection of accessories – combs, decorative boxes, furniture – made infusing hair into natural resin. Tomas Vailly, within his graduation project "the Metabolic Factory" turned human hair into a new leather-like biomaterial melting it with sodium sulfite and glycerin. With the project "The colour of Hair" instead, Fabio Hendry and Martijn Rigters used hair to develop an innovative printing technique which turns it into an ink to be used on a variety of metals. Also dust can become a valuable material as illustrated by Agùsta Sveinsdottir who turned it into a jewellery collection, or Matilda Beckman who mixed dust from vacuum cleaner bags and wood glue and made it into a table and chair. In the last few years, the Graviky Labs of MIT have been working on "Air Ink", an ink obtained from air pollution generated by burning fossil fuels. They developed a device able to capture air pollution and turn the captured particulate matter into a safe, water-based ink for different applications and writing tools. In addition to the examples mentioned, we can find many projects which give a second-life to pollutants such as oceans' plastics. Adidas and Parley for example, partnered to retrieve plastic waste from shorelines and turn it into a thread woven to create running shoes. This kind of initiative is essential to raise awareness on the topic in this historic moment, however it seems to be inadequate as long-term strategy when the plastic waste is used to make products which will rapidly turn into new plastic waste, polluting our environment again in a never-ending process.

18.

19.

18. Precious Plastic
19. Precious Plastic, shredding machine
20. Precious Plastic, shredded plastic chips

20.

21. Bioshades by Cecilia Raspanti, Textilelab Amsterdam - Waag Society: creative exploration at the intersection of fashion and biology, aimed at the research of alternative and non polluting ways for textiles dyeing using bacterial pigment extraction and direct bacterial growth

2.4.2. Growing

With the spread of biofabrication designers turned their attention to living matter, acting new forms of interaction and collaboration with microorganisms as source for materials production. They started to create the conditions to foster and harness their natural growth and reproduction processes in order to “harvest” their fruits in the form of materials and products. This kind of production system represents an inexhaustible source of circular materials, since the growth conditions of many microorganisms can be easily replicated in different areas and climatic conditions around the globe.
Micro and macro algae for instance, are one of the most renewable organisms on the planet, they can be grown worldwide and can often thrive also in the adverse conditions brought by climate change and sea acidification. Moreover they are beneficial for the environment fostering the life of many marine species, essential to life on earth for the oxygen production, and have always proven extremely versatile to us humans, finding application in many fields from food to medicine, and today also in the world of materials.
There is a variety of substances extracted from algae, one of the most known is probably spirulina which is widely used in food related products but represents also a good source for natural dyes production because of its blue-green colour. Agar agar, also used in food products as gelling agent, is derived from different kinds of red algae, and it’s made of two components: the linear polysaccharide agarose and a heterogeneous mixture of smaller molecules called agaropectin. It’s gel-forming property makes it suitable for the production of biopolymers and its use as a binder in the production of bio-based composites.
Ari Jónsson with “The Agari Project” realized a water bottle made up of agar which starts to decompose as soon as it’s emptied from its content while keeping water fresh when full.
Another wonder substance is Alginate, a polysaccharide abundant in the cell walls of brown algae which forms a viscous gum when hydrated, and if used in combination with Calcium Chloride as curing agent a shrinking reaction occurs which turns it into a waterproof biopolymer. The water resistance opens a window of new opportunities for its application, as shown by the edible water bottle (or rather bubble) “Ooho”, an sphere made of a thin alginate membrane filled with water.
Besides algae derivatives, seaweed – or macro-algae – can

be also used in their entirety as vegetable fibers source or as textile-like material. Some examples are Kelp, which has an high growth rate and grows in underwater forests, or Posidonia oceanica, also known as Neptune grass, an endemic species of the Mediterranean Sea. From its foliage are originated balls of fibrous material called Egagropili, and both the foliage and the felt-like balls are used for material production.
The designer Julia Lohmann established the "Department of Seaweed", an interdisciplinary community exploring the marine plant's potential as a design material. Her "Oki Naganode" is a large-scale installation made of Japanese Naga seaweed, treated to remain flexible like a translucent leather, stretched over a modular framework made of cane and aluminium.
Also terrestrial plants can become collaborators for material production as shown by Diana Schrerer's researches on plant-root systems and how to control the morphology of their growth in order to obtain specific geometries. After the growth, the interwoven roots can be harvested in the form of a textile sheet. Moving to more futuristic scenarios, with her concept "Biolace" Carole Collet shows the potential of the collaboration between design and synthetic biology, imagining to genetically engineer plants in order to program their root to grow according to specific shapes, producing at the same time food and textiles.
One of the protagonists in the emerging field of biofabricated materials is Mycelium. It is the vegetative part of a fungus and its structure consists in a tangle of filaments. It is vital in terrestrial and aquatic ecosystems for its role in the decomposition of organic compounds, and it cooperate with plants in the mutual symbiotic association called Mycorrhiza, favouring tree growth while feeding fungus with carbohydrates. Mycelium grows feeding on organic matter, and for this reason is often used in combination with agricultural waste used as a substrate for material production. During their growth the mycelium filaments will envelope and embed the organic matter, and different kinds of substrates will result in materials with different properties. It can be also be grown alone as pure Mycelium to get a waterproof flexible textile which represents a valid alternative to animal leather.
Other important microorganisms for biofabrication are bacteria. Some kind of strains can naturally produce coloured pigments and are therefore used for dyes making as an alternative to synthetic and plant-based dyes. Natsai Audrey Chieza, founder of Faber Futures, realised a collection of fabrics dyed using Streptomyces coelicolor. Flavobacteria instead, when growing in colonies can produce colours derived from structural effects rather than pigmentation, and are being genetically engineered for the production of paints and coatings. Besides colours and dyes, bacteria are used also for the production of biomaterials. Acetobacteria indeed, in collaboration with yeasts in a symbiotic culture, can produce layers of nanocellulose through a fermentation process commonly used in the food industry for kombucha production.
Another promising sector is the one of lab-grown materials: after the first researches on lab-grown leather by Suzanne Lee, experimentations on other animal derived materials has followed. Furoid is a Dutch biotech company which focuses its researches on cell-based fur, wool and cotton, grown in vitro without harming nor killing any living being, besides cutting emissions which normally are produced within the traditional manufacturing of these materials.

2.4.3. Alive

Besides representing novel and precious collaborators for material fabrication, living organisms have become themselves matter of the project. As stated by Miodownik, what most distinguishes living matter from non-living one is that in the first case we can find an "extra degree of connectivity between the different scales", which means that living materials have the capability to actively organise their internal architecture setting up communication between the different scales of the organism (2013).
What results therefore are designs which are literally alive that we could define "bio-smart" (Lucibello et al., 2018), responsive intelligent materials able to react to changing external conditions. "Bioskin" is a living breathing textile developed by the BioLogic research group at MIT Media Lab. Through the integration of living materials in the textile design, the fabric can act as an interface between humans and the environment, just like real skin. The bacterium Bacillus subtilis natto indeed, reacts to body heat and sweat, resulting in a self-ventilating garment which opens and closes its "pores" to cool down overheated areas of the body.
Microbial induced calcite precipitation instead, is a natural cementation process of extremophiles bacteria – which can survive in extremely harsh living conditions – as Sporosaracina pasteurii. Henk Jonkers from Delft University harnessed such process to rea-

22. Bioconcrete, self-healing concrete, Henk Jonkers







23. Posidonia Oceanica
24. Kelp seaweed
25. Julia Lohmann, Department of Seaweed, Helsinki Design Week 2019
26-27-28. Fungal mycelium
29. Growing Lab - The Future of PLa-stic Exhibition, Officina Corpuscoli for Fondazione PLART

30. Ambio by Teresa van Dongen

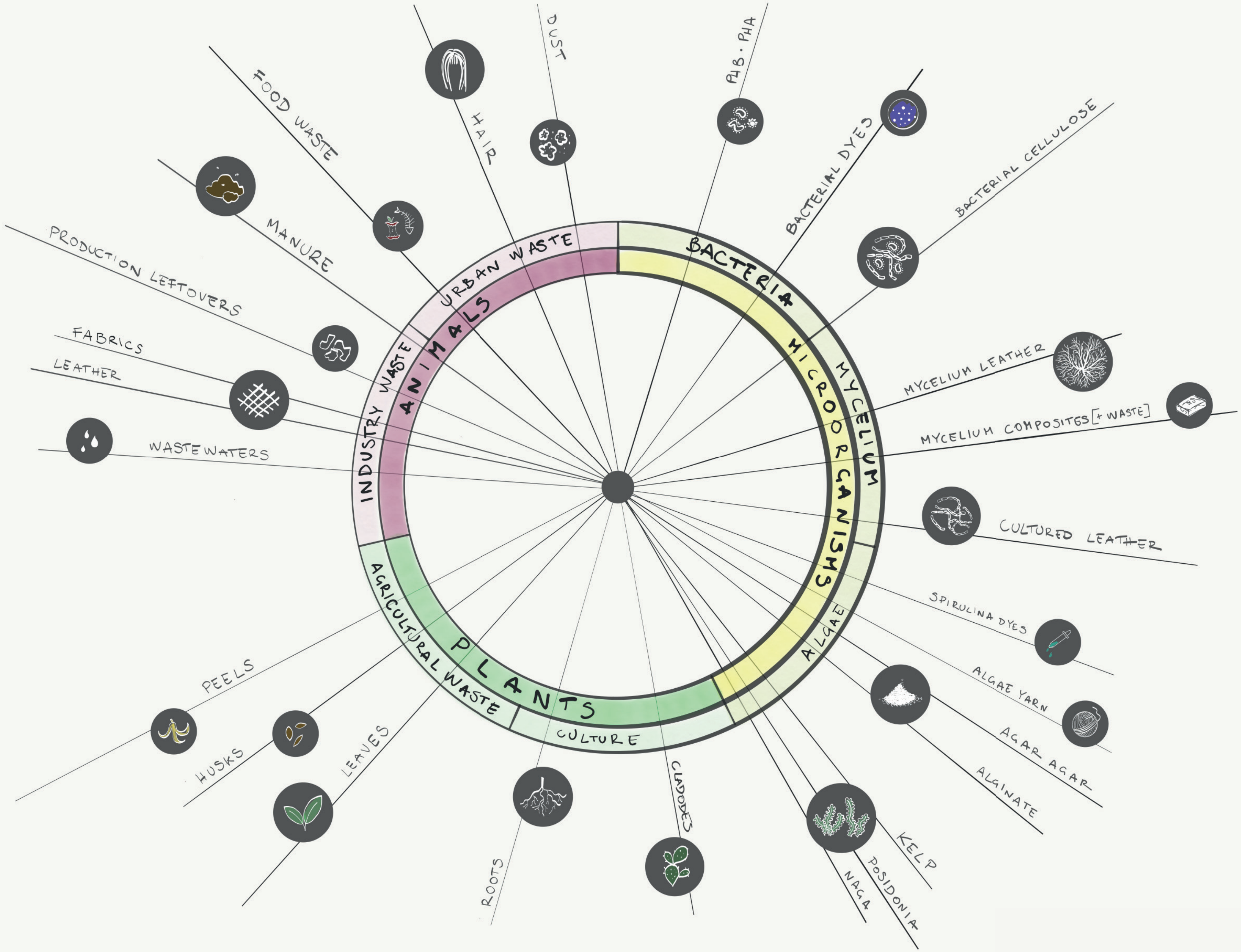
31. The Living thing by Jacob Douenias and Ethan Frier

lise a self-healing concrete: embedding such microorganisms who can naturally produce limestone in the concrete, they will fill and seal cracks and holes strengthening weak areas. The same process is used by Damian Palin within his project "a radical means" to cast everyday objects as stools.
Living organisms are therefore agents of who act on the micro scale to transform matter and energy around us. In addition to material production, they prove to be good collaborators also for electric and light energy production.
Biophotovoltaic systems use microorganisms to harvests light energy and produce electrical power. Researchers from Imperial College London, the University of Cambridge and Central Saint Martins have succeeded into turning Cyanobacteria – photosynthetic organisms – into an ink which can be printed on paper and produce small amounts of electric energy. The project "Moss Table" by Carlos Petrarca, Alex Driver and Paolo Bombelli, intends to illustrate the potential of biophotovoltaic technology through a coffee table containing a living moss layer able to produce enough energy to power small electronic devices. "Latro Lamp" by Mike Thompson is a living lamp powered by energy produced through algae photosynthesis. Filling the lamp with water, placing it outside during the day to provide sunlight and breathing inside it to provide carbon dioxide, will activate the photosynthetic process and produce electric energy which will be stored in a battery and used at a later time.
Bioluminescence instead, is the visible creation of light by an organism through a biochemical reaction. This phenomenon is the result of the oxidation of luciferin, a light-emitting molecule, together with a catalysing enzyme, either a luciferase or a photoprotein. It has been witnessed among insects – the best known are fireflies –, mushrooms, bacteria, algae and deep see marine animals, and is now been using in product design for the making of living lamps and lighting systems. In 2010 the Cambridge team developed the "Bacterial bubble lamp" for iGEM competition, made from a culture of genetically engineered E. coli. Shaking the lamp will expose bacteria to oxygen, and activate the glowing effect emitting a soft blue light. This process was implemented into a design product in 2014 by Teresa van Dongen with "Ambio Light", a lamp which is not static but in motion, in order to to feed the oxygenation and keep the light glowing. The design studio Bompass & Parr, using pyrocystis bioluminescent algae has created "Mermaid's Lunchbox", a collection of jewels that glow when shaken in response to body movement.

Looking at the current scenario, we can easily imagine a future where we will share our houses and cities with microbial systems in a symbiotic co-existence. The project "Bioluminescent devices for zero-electricity lighting" by Eduardo Mayoral, prefigures the use of a combination of Vibrio Fischeri bacteria which glow in the dark and Pyrocystis Fusiformis algae that glow when excited by movement, for public ambient lighting. "The Living Things" installation by Jacob Douenias and Ethan Frier, shows a domestic environment made of furniture embedding glass bioreactors containing spirulina algae cultures, that can be harvested and used as homegrown food source. Design studio MADLAB created "Bacterioptica", a living chandelier containing organisms and bacteria from the house and family members. It is made of illuminated petri dishes where the bacteria samples collected by the user are cultured, and depending on the type and colouration of each sample the lighting effect will be slightly altered.

FUTURE MATERIALS

circular, abundant, biofabricated



Nothing is created, nothing is destroyed, everything is transformed

From Humans' macro-scale to microorganisms' micro-scale, living organisms act transforming matter and energy around us.

Future materials will be produced through living organisms' biological processes, whether they microbes, plants or animals, as well as through waste resources from humans' systems production and consumption.

The map includes materials with diverse environmental impacts, as materials which require particular conditions or long time to biodegrade and compostable materials that you can throw in your backyard garden and they will turn into humus for your plants.

Moreover there are materials which come from industries which are in themselves unsustainable, as any livestock industry byproduct as leather or gelatine, which then shouldn't be produced anymore in the allocentric future we are imagining but are still part of our current industrial and urban technical nutrients' flows, and therefore need to be taken into account.

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CHAPTER 3 # FUTURE DESIGNERS

ABSTRACT

The figure of the designer was originally characterised by a direct relationship with matter, and the activity grounded on practice and tangible experience, opposed to the abstract realm of thought. The two opposed realms of making and thinking came together in the figure of the modern designer, for whom making is thinking. The subsequent multiplication of materials and the shift from the experiential to the abstract dimension, brought a disconnection from the concreteness of matter and processes, and therefore from the reality of the context within which we operate.
Currently a new mindset is emerging within the design culture, which shifts the overall attention from the final output back to the generative process, with all the implications deriving from it. It recognises the transformative nature of design, which has to understand and adapt to the circularity and cyclicality of Nature. The return to direct experimentation entails a reappropriation of the production stage: DIY production protocols take the place of material libraries as design tool through which acquiring knowledge – that returns to be experiential rather than theoretical – about materials, in a new hybrid dimension halfway between a kitchen and a science laboratory.
As our current inquiries change and expand in range and complexity, there is the involvement of new disciplines, skills and expertises in the design activity. We need to broaden our view, collaborating and contaminating: think systemically and act collectively. Within the transdisciplinary dimension of biofabrication science and design blend and hybridise. Designers have to be able to step outside disciplinary boundaries without however losing the specificity of their contribution, integrating the analytical approach of science which develops vertically, with the synthetic approach of design which spreads horizontally as connective tissue. Moreover, they need to abandon the illusion of full control and accept a certain degree of uncertainty in order to develop new efficient strategies to deal with complexity.
Future designers must be able to change scale from micro to macro while maintaining the awareness that one is part of the other, discarding the anthropocentric perspective in favour of a planet-centric approach to design.

3.1. The evolving role of designer

3.1.1. From Selectors to Makers

In the beginning, designers were those having knowledge and expertise with regard to materials and techniques. Their figure was close to the craftsmen one, characterised by a direct relationship with matter, and their design and manufacturing activity arose from the specific features and constraints of the materials they worked with. Such figure, grounded on tangible experience and practice, was opposed to those working in the abstract realm of thought. With modern science, the dichotomy between the opposite yet complementary sides of theory and practice finds a synthesis in the modern designer: an hybrid figure who has thought as starting point and matter as constraint, who builds abstract knowledge learning from books, but has the possibility and the time to learn in the field (Manzini, 1986). Hands and mind work together affecting each other, since “making is thinking” and at the same time, as remarked by Kant two centuries ago, “the hand is the window of the mind” (Sennet, 2008).
In the following years the materials at our disposal proliferated and, with the knowledge gap brought by hyper-choice (Manzini, 1986) – which made the abstract knowledge of materials the only possible way – and the consequent birth of material libraries, the figure of designers got closer to the one of the engineers, shifting from a direct experiential relationship with matter, to a conceptual and encrypted one. Subsequently, with advances in material science, materials ceased to be given entities upstream of the project, something to select from a preexisting palette, and become themselves subject of design. The opportunity to modify their features at the nano scale other than micro and macro scale, to change their physical or chemical composition, gave rise to an infinite range of possibilities, going from hyper-choice to hyper-design (Lucibello, 2009). Designers started getting involved in the very early stages of the project, contributing to the design of materials themselves besides products, and designing materials and their features according to the project requirements.

The broadening of design possibilities in the field of materials, brought in many cases a condition of alienation and disconnection from the concreteness of matter and processes. Such disconnection pushed designers away from reality and from the context in which they operate: the planet Earth. This is therefore at the root of the environmental repercussions of design, in terms of resources used, impact of processing and waste generated, that we can no longer ignore. In recent years, designers started to reclaim the production process of materials, exercising their ability to transform matter with their own hands and mind. This tendency, which La Rocca defines "neomaterico" (2016), has brought designers back in the lost experiential laboratory dimension, and shifted the overall attention from the final output back to the generative process, thanks to the growing awareness that "design is not shape", but is also all the implications of who and how will produce it (Bovo, 2019). So designers are today approaching to matter around them from a different perspective, looking at waste as a new valuable resource, implementing diy processes for material production, and developing also new tools and protocols for manufacturing. Moreover they started to collaborate with living organisms to scale up their natural growth and reproduction processes and harness them for the production of new biodegradable materials with growing design and biofabrication. This is laying the foundations for the spread of a new mindset and cultural model, through which recognise the transformative nature of design, and explore the potential offered by the circular and cyclical model of nature, rather than pushing design beyond the limits of what is possible, oblivious of the consequences and boomerang effects of our actions.

3.1.2. Collaborations, Contaminations

Design is an activity in constant evolution, its identity has never been fixed and its range has never had a strict boundary. For many years it has been considered as "the conception and planning of the artificial" (Buchanan, 1992), but with the dissolution of the boundaries between nature and artifice we are continually changing our understanding of what design is.
As a discipline, it has always based its activity on the collaboration between knowledges. It has an "heteronymous nature" and is aimed at "understanding and organising different knowledges in the concrete dimension of an artefact, product or service" (Riccini, 2013). It can be considered a "synthetic discipline able to close the loop of innovation" and condense the results of scientific research into future scenarios and tangible artefacts attributing them value and meaning (Lucibello, 2018; Ferrara, 2015). Through design, the analytical fragmentation between multiple expertises and disciplines can find a synthesis, in a twist of knowledge and know-how, concreteness and abstraction, ideas and matter.
For many years designers have been used to interact with disciplines such as psychology, sociology or philosophy – just think, for example, to Gestalt Theory, Semiotics, Cognitive Ergonomics –, as well as pedagogy and education – suffice it to recall the work of Bruno Munari and Enzo Mari. At the same time, the succession of technological and scientific innovations over the years, resulted in the involvement of new disciplines and acquisition of new skills – robotics, cybernetics, computer science, material science, nanotechnologies, to mention a few. In order to operate in a transverse way and engage in dialog with such different worlds, designers have to act as "humanists used to work with others" rather than "hyperspecialists" (Bassi, 2017), and collaborate to build a "knowledge of knowledge" to better understand ourselves and the world we inhabit (Morin, 1986). To make this happen they need two essential tools: a "microscope" to understand how things work to the last detail, and a "macroscope" to understand relationships and interconnections with culture, society and environment (Manzini, 1986).
The complexity we deal with indeed, can be properly managed only if faced from multiple perspectives, looking at issues from different angles in order to give back a complete vision without falling into over-simplification, thinking in a systemic way and acting collectively. This awareness is leading towards the annihilation of disciplinary boundaries, and the spreading of inter, trans and anti disciplinary[1] researches and practices.
The contamination with other disciplines, and in particular with science, has always been a fertile ground for innovation. However, one of the more interesting outputs of such contamination is the production of knowledge rather than objects, and the seek for a qualitative improvement through the sharing of such knowledge. Indeed, advances in the science field have given us a greater understanding of how the world we inhabit works, moving away from the metaphor of the machine (complicated) in order to adopt the one of the organism (complex). Shifting the focus away from the human scale, moving from microcosm to macrocosm, we can

1. The term antidisciplinary was coined at MIT Media Labs, referring to a research approach where the project isn't the result of the sum of multiple disciplines but something entirely new which doens't fit within traditional academic discipline

see that every organism including ourselves is made from, and at the same time is part of, complex systems interacting one another. In ancient times, this concept was referred on the macro scale to the relationship between humans and the universe. According to Hermetic philosophy indeed, man and universe are two entities where one is a scale replica of the other and, for this reason, they constitute an indivisible totality where the parts are in relation with the whole. With modern science, in the '70s, this concept found validation in the mathematical field with Mandelbrot's study on fractals which proposed the holistic model of pattern repetition both in the micro and in the macro scale. Fractals are characterised by internal homothety and so they replicate their morphology analogously at different scales. The net structure made of filaments developed by the Physarum Polycephalum mould for example, has been recently used by cosmologists to develop an algorithm able to predict the distribution of the cosmic net structure which connects galaxies (NASA, 2020).
As our current inquiries change and expand in range and complexity, there is the need for the involvement of new disciplines, skills and expertises in the design activity. The biofabrication revolution indeed, brings along with it a brand new way of designing. The design history, the history of the relationship between humans and matter, is the history of the relationship between the intention of social actors with the ability to choose, and the functioning of the complex system they are part of (Manzini, 1986). Today, with biofabrication, to the complexity of the social and environmental systems we have to add another degree of complexity, given by the living system with whom we interact.
The collaboration with complex living systems equipped with their own autopoiesis, allows designers to experiment firsthand the principle of ecology of action, according to which "from the moment an action enters a given environment, it escapes from the will and intention of that which created it, it enters a set of interactions and multiple feedbacks" (Morin, 2008). This principle has universal value and is valid at every scale, but often humans can barely perceive what bears consequences far in space and time. Climate change is a case in point: the Earth is a complex system characterised by systemic inertia – which means the input loses its time correlation with the output – so the effects of any action are delayed, and when they will become visible it will be already too late to go backwards. On the contrary, experiencing this principle directly on the small scale of biofabrication – which allows them to see in a shorter timeframe the results of any action implemented – can push them to abandon the illusion of full control and accept a certain degree of uncertainty, and so to develop new strategies to deal with complexity.
Future designers will have to move between microcosm and macrocosm, developing the ability to change scale while maintaining awareness that one is part of the other. From atoms to cosmos, from the principles of microbiology and genetics to the interactions between the complex ecosystems constituting our habitat, it is essential not only to understand what happens at each scale, but rather to grasp relations, interactions and connections. This will guarantee a greater awareness on the impact that designers' intentionality has on the surrounding world, and push towards new forms of collaboration among organisms as part of the same whole.

3.2. Bioneers and D.I.Y. Biomaterials: material labs and bio-makers

The idea of "new materials" is usually referred to the transformation of what until then was traditionally intended as matter (Manzini, 1986). The technological and scientific research indeed, develops much faster than the socio-cultural structure, and any transformation in the field of materials which doesn't leave enough time for its cultural sedimentation and elaboration is then categorised as "new". However, there has always been a wide gap between the research on new materials and their industrial development, which is in fact characterised by long lead times. Lycra for instance – innovative and revolutionary synthetic textile created in the '50s by the chemicals multinational Dupont – required ten years of research and development and three additional years (beside million dollars investments) for market placement, followed by around sixty following years of constant innovation (Lucibello & Montalti, 2020). Aerogel's inventor Steven Kistler died in 1975 "having never seen his most wonderful material find a place in the world" (Miodownik, 2013). Invented in 1931, Aerogel was in fact used in the first place as thermal insulator by Monsanto with little success, and later implemented into applications with ever decreasing relevance (as in inks and paints to create a matte finish) until they completely stopped producing it. Many years later, in later '70s, it was rediscovered by CERN scientists as a wonder material for its properties, and then used by NASA for space flights as thermal insulator in the beginning, and then to collect and study interstellar dust.

Talking about bio-based materials, in the previous chapters we saw how research on the industrial development of biopolymers, which have been shyly peeking out on the market only in the last few years, dates back to the 1970s. Moreover, usually new materials are implemented as imitation of "traditional" ones to which we are accustomed, before finding suitable applications that give value to their identity and peculiarity. An emblematic example are plastics which, initially, spread on the market as imitation of nobler materials such as wood, before disclosing their eclectic nature revolutionising the plastic industry, affecting peoples' behaviours and giving birth to new typologies of products (Cecchini, 2004).

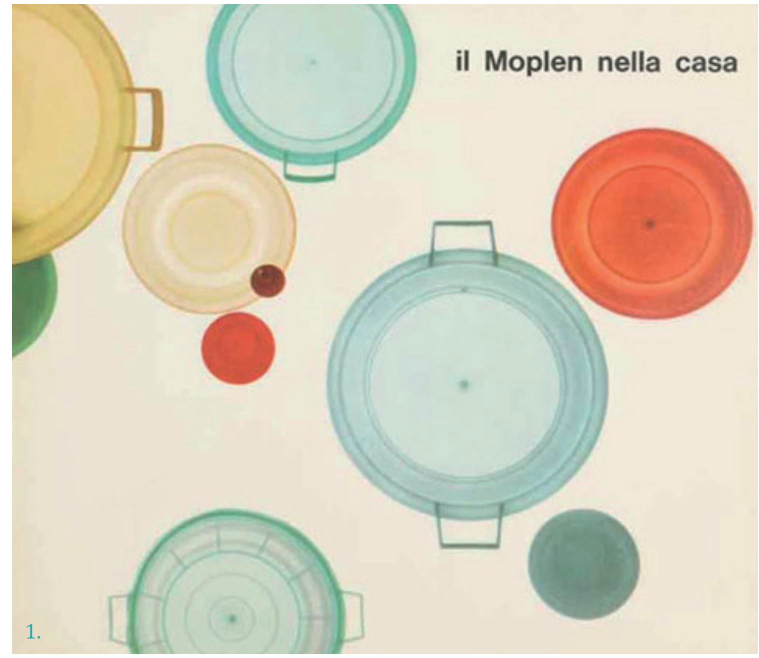
Today, with the biofabrication revolution, we are going through an exploration phase as regards biofabricated and bio-based materials, characterised by the open-source development and sharing of "recipes" for DIY production. Material libraries are so being replaced by "cookbooks" or digital archives, which provide designers with the knowledge necessary to experiment the self-production. An example of this is Materiom, an online platform which provides open data about materials following the principles of the regenerative circular economy, and so zero-waste and made from locally sourced abundant biomass. The platform consists in a collection of recipes supplied by an international community of designers, scientists, engineers and artists, with the aim of accelerating and fostering the material development.

Within such exploration phase, designers are bridging the knowledge gap on the subject through first-hand experience, and layering this experience over time in order to shape the still unexplored identity of novel materials. We are therefore witnessing a return to direct experimentation with the re-appropriation of the production stage, in a new hybrid dimension halfway between a kitchen and a science laboratory. A dimension characterised by centrality of processes, and so by the need to learn and understand laws and principles which determine the functioning of the matter that we interact with. Only through an hands-on approach is possible to understand matter, its behaviour and potential, and the active dimension of making is then essential to gain a practical understanding and be able to develop a theoretical perspective.

Apparently, it may seem that designers are approaching biofabrication as bricoleurs or amateurs makers, but actually they represent an avant-garde trying to do by itself what large-scale industry doesn't want or isn't able to do yet: self-producing new materials designing the structural features besides the aesthetic ones, with the aim of finding alternative solutions to materials currently in use, which have proved to be unable to meet the changing needs of today's society (Doveil, 2020). The "bioneers" – biofabrication pioneers – instead of passively waiting for a better world to come, are therefore actively working to create it, pushing the development and application of new bio-based and bio-fabricated materials bypassing the standard stages of industrial development, through what we can define a design driven material innovation.

Besides the best known biodesign-driven and research-based mul-

tidisciplinary practices such as Officina Corpuscoli in Amsterdam (NL) or Faber Futures in London (UK), a growing number of material labs is sprouting up across the globe, sharing recipes and building open-source material archives. Shifting from tinkering to thinkering, they act as innovation incubators, interacting with each other in a widespread network involving fablabs, workshops, universities, individual designers and local communities, and engaging in a constructive co-operation which gives rise to a process of collective advances (Antonelli, 2011; Brown, 2007).
Fabricademy for example, is a course based on distributed education focused on innovation in the textile filed. It takes places simultaneously in different fablabs worldwide and provides insights on the latest technologies and materials from which to experiment and imagine new applications for fashion design. The Chemart Summer School by Aalto University in Espoo, Finland, instead, focuses on the interdisciplinary research on innovative uses of cellulose and wood from the Finnish forest industry, each year releasing a Cookbook which showcases ideas and recipes for hands-on material experiments. In Rotterdam, Netherlands, the BlueCity Lab is a facility with workspaces and laboratories in support of bioneers, as well as a platform for circular economy entrepreneurs to connect and scale-up projects. Moving to the opposite hemisphere, in Valdivia, Chile, we can find Labva, an independent community biomaterials lab which bases its activity on the promotion of biodiversity through the use of local resources. Developing both grow-it-yourself and cook-it-yourself materials, their aim is to bring science closer to the local community.
As we can see, unlike in the past, today the material innovation is not being pushed forward by large multinational companies, but by start-ups, individual design practices and small local realities. This is because the innovation is not only in terms of matter, but also in terms of processes and systems, and is therefore characterised by new bottom-up approaches which are questioning the traditional industrial system based on perfection, mass production, standardisation and globalisation. The design-driven approach entails the exploration of matter also from the cultural and semantic perspective, and therefore an investigation on its ephemeral nature, uniqueness, raw and imperfect aesthetic as elements of a new language that expresses the cyclical nature of life on Earth.
In this stage, it is fundamental to not repurpose logics and models of the past, as for example the design and application of



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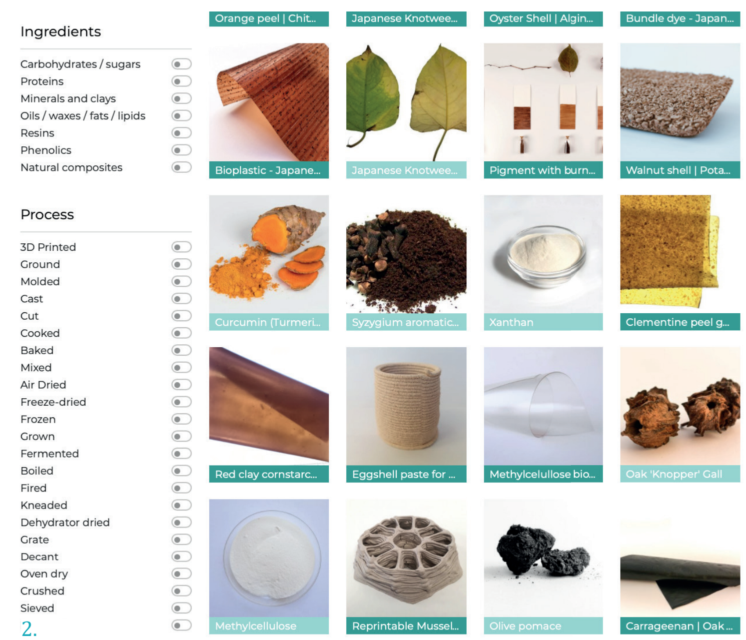

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1. Il Moplen nella casa, Annuncio pubblicitario, Brochure e Regesto prodotti (progetto grafico: Giulio Confalonieri, Ilio Negri), Montecatini / Rizzoli Grafica, Milano 1961 | © Montecatini / Giulio Confalonieri, Ilio Negri, courtesy Rizzoli Grafica / Aiap / CDPG - Centro di Documentazione sul Progetto Grafico di Milano

2. Materiom digital material library, materiom.org

3. CHEMARTS Cookbook Foam experiments, Aalto University. Photo by Eeva Suorlahti

4. LABVA - Laboratorio de Biomateriales de Valdivia, labva.org

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apparently "natural" materials which are actually chemically treated with harmful substances – inks and chemical additives used on paper, synthetic dyes and colourants on textiles, etc. – which cannot but bring consequences not far from the crisis that we are currently experiencing.
What we need now are not incremental changes but radical transformations, and therefore not only to apply the traditional way of designing to new biomaterials, but rather grasp the opportunity to radically change the way of thinking, designing and so consuming, facing resources and waste management, lifecycle, time and durability, and looking at each single product as part of a system, intersection of an entanglement of metabolic fluxes.

Material libraries

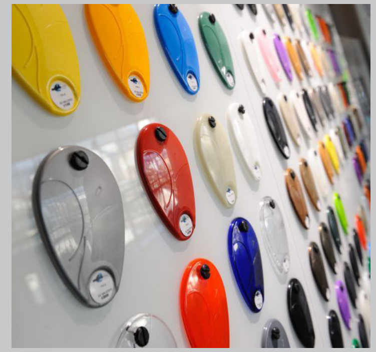
Dissemination and Communication

Material libraries represent the evolution of technical archives and manuals, and were born in the 90s as a consequence of the multiplication of materials available and the growing complexity brought by the possibility to specifically design tailor made materials, according to particular needs and performance requirements. The world of material wasn't anymore a set of given materials but had turned into a "continuum of possibilities" (Manzini, 1986).

This made impossible to acquire an in-depth knowledge, also because any knowledge acquired about materials usually "is not transferred from maker to user and materials needs are not relayed back to manufacturers" (Wilkes, 2011).
So, in 1997, George Beylerian founded the first material library and named it Material Connexion, highlighting its ability to link and connect designers and architects with the wide range of materials available and the manufacturers who produce them. Material Connexion's archive consist of an online database and physical locations scattered all over the world, from America to Asia. Material libraries "can be seen as part of a larger project encouraging interdisciplinary transfer of knowledge about materials in order to control their development" (Wilkes, 2011). They create indeed a network among the different professionals revolving around the world of materials, establishing communication between scientists and designers, blending technical, sensory and cultural knowledge. In this way they can bridge the knowledge gap about materials, and at the same time the language gap between disciplines.

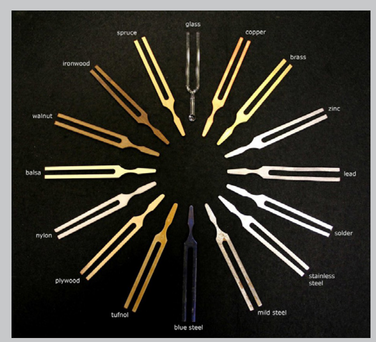
In the first place the material world was subdivided into well defined material families, each having specific characteristics distinguishable from the others. Therefore, besides all-encompassing material libraries, ever more specialised libraries started to spread, each focusing on specific material families or categories, as for instance the French library Materiautech dedicated to plastics.

With the growing multiplication of materials, families started to overlap until the vanishing of such specific subdivision. At this point, rather than specialise on families, novel material libraries started to develop around thematic areas. This category includes arTec in Venice, IT, which is dedicated to architectural materials and products, the French Innovatheque, dedicated to innovative materials just like Material Driven in London, UK, that also pays particular attention to the environmental impact, or Matrec in Ancona, IT, specialised in recycled and circular materials. In recent times material libraries are becoming more and more a tool for design inspiration, not including necessarily just materials that are currently in production and available on the market but also materials still in the research stages, which can represent a creative input for the project and at the same time can find innovative applications thanks to designers' intuitions. An example is the Hylocene section of Material Design Point, SAPeri&co's material library at Sapienza University in Rome, IT.



Materiautech, Lyon, FR
Polymer Samples

Matrec, Ancona, IT
Bioplastic from rice husks



UCL Institute of Making, London, UK
Tuning Forks of different materials

Most material libraries as Material Connexion require payment to be accessed preserving the elitist aurea which used to characterise archives in the past, and are therefore addressed to companies, with no interest to inform students about new materials and latest possibilities. Opposed to this approach we can find also some material libraries as the Dutch Material District (previously Materia), which provide open access and are then established as a shared archive, a common good available to scholars but especially students.

Generally material libraries display their materials placing a flat material sample sticked onto a descriptive sheet, or in the case of online databases pictures and description of the material, providing in both cases mainly an analytical textual knowledge. However the experiential aspect when talking about materials is fundamental and hands-on experience is needed to grasp material features that can't be classified, making the physical experience necessary for an holistic understanding.
At UCL Institute of Making is possible to experience a new form of fruition: Zoe Laughlin developed "material-object" sets which take functional object forms such as cubes, spheres, tuning forks and bells, and make multiple versions of them each using a different material. The goal is to use these sets as an interdisciplinary research tool to explore "the relationship between form, function and materiality" and understand how during the material experience "their chemical, physical and mechanical properties relate to their sensory and aesthetic properties" (Wilkes & Miodownik, 2018).

Many material libraries are therefore acquiring an increasingly experimental dimension, moving towards the model of "materiolab" (Migliore, 2015). Materiability for example is specialised on emerging materials, and on its website provides a tutorial section for material experimentations. The experiential and experimental dimension has acquired a growing importance with the spread of DIY and biomaterials making, thanks also to the fact that the needed components are readily available and many processes can be easily reproduced at home using kitchen tools. With biomaterials and biofabrication then, we are shifting from material libraries to cookbooks and archives as Materiom, which collect recipes and procedural indications to self-experiment with material production thereby giving way to designers' creativity and invention.

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I. UCL Institute of Making, London, UK
II. Tutorials - Materiability Research Group, Anhalt University of Applied Sciences, Dessau, DE

3.3. Design in Lab

The trespassing of designers inside science laboratories with biofabrication, brings us into a new trans-disciplinar dimension where the hybridisation and contamination with science can generate invention. The crucial question is how far in this context the designers' range expands, and which are instead its limits. The main risk indeed, is to fall into hyper-specialisms, pose ourselves as pseudo-biologists, chemists or engineers doing poorly what somebody else can do better. The evolution of design and the calling into question of its identity has to some extents turned the term design into a "suitcase world", acquiring so many meanings to lose meaning (Ito, 2016). In this way, what we lose is the specific contribution that design can provide in the trans-disciplinary context, within which it isn't a director supervising from a privileged position, but a synthetic element acting from the bottom to connect the many different elements of a system and condense them into something unitary (Trebbi, 2020).

Trans-disciplinarity allows to face the complexity of global challenges, summarising the multiple perspectives of different knowledges without over-simplifying but giving back their complexity in an understandable way. The only way to face such challenges is indeed to step outside disciplinary boundaries and act contaminations, without however losing the specificity of the contribution which different areas of knowledge can provide. When it comes to design, its contribution in the new laboratory dimension of biofabrication, straddling biology and design, is in the first place the inductive approach. On the contrary of science, design operates opposing induction to deduction, experience to logic, and synthesis to analysis. The two different approaches are therefore complementary, and so we need to implement "innovation and experimentation processes where science and design get closer, intersect and fertilise" (Langella, 2011).

In the field of materials, the experiential approach grounded on senses and perception is an essential element that we can't get along without. The Japanese samurai were legendary in forging superior quality steel swords, and their secret was that over the years they have been refining their ability to distinguish between hard but brittle high-carbon steel (used for the center of the sword) and tough but soft low-carbon steel (perfect to make very sharp edges), only by how it looked, felt in their hands, and sounded when struck, without any knowledge of the chemistry behind that (Miodownik, 2013). The involvement of design in the early stages of development of materials and processes, allows to design the overall "material experience" (Karana et al., 2014), twisting the technical-productive features with the aesthetic-perceptual ones. So we need to hybridise scientific rigour with trial and error, identify common protocols and overcome the "difficulties of language" (Ashby, 2002), communicating visually other than verbally, and understand the relationship between physicochemical features of materials' structure and emotions generated from their perception. Moreover, the unexpected results of the processes implemented, which for the scientist would represent mistakes, failures, or worthless information, can instead trigger new ideas and become the driving force for innovation.

Another distinctive element, which characterises the design contribution in the trans-disciplinary field, is the envisioning ability that allows to prefigure future and futuristic scenarios acting on different scales, combined with the systemic view that looks at interconnections and pushes us to ask ourselves why should we do something, what consequences it has, and therefore avoid the experimentation for its own sake, unconcerned about long-term and long-range repercussions, as often happens.

Design is a transformative force which acts as a "trim tab"[2] – a small mechanism used to stabilise an enormous ship or aircraft –, and therefore is able to bring about small changes that can have long-range impact on the wide scale (Antonelli, 2019), a power which demands to be exert wisely and consciously. In doing so, its main instrument is perception as vehicle of values and meanings. Perception indeed, as result of the cognitive processes originating from sensations, is a twist of material and immaterial elements. It is a mix of physiological factors related to senses, psychological factors related to emotions and cultural factors related to meanings attribution (Zuo et al., 2001). Aesthetic-perceptual features, involving the user on the emotional level, are therefore essential for the appreciation and consequent diffusion of new materials and products (Sauerwein, Rognoli, & Karana, 2017; Zafarmand, Sugiyama, & Watanabe 2003). Furthermore, they can on one hand reflect the current value system of society, but on the other hand they can push the user towards to new values. Just look at the aesthetic of recycled materials, which was once associated to low-value and cheap matter while today is a quality symbol expression of values related to ecology and ethics. Today with biofabrication designers are acting analogously, pushing society to a novel mindset communicating the value of imperfection, discarding the idea of standardisation and aesthetic flawless shifting from mass production to unicity of nature's processes.

Designers so play an essential comunicative role, placing themselves between research and society and "culturalising" scientific innovations (Manzini, 1990). In the field of biotechnologies in particular, "design allows to defuse the fear factor of science and infuse it with wonder" (Lee & Bongaerts, 2019), bringing the results of scientific research outside from libraries and laboratories making them available to society.

2. Richard Buckminster Fuller introduced the idea of the trim tab as a metaphor for personal empowerment in a Playboy interview of 1972, in order to explain how the individual is connected to society and therefore each one can make a difference. He used to say "call me trim tab", an expression that was engraved even on his gravestone

3.4. The Design of Nature: Biodesign and Ethics

With biodesign and biofabrication nature is involved in the design process as a co-worker but also as the very object of design, with an approach that looks at living matter as a "programmable material" (Van Der Leest, 2016). We are today in the era of "biology 2.0" or "post-genomic biology" (Carr, 2010), where the understanding of DNA sequencing, genetic and biological processes, brings the possibility of their manipulation, marking a shift from the search for knowledge – which was the original mission of biology – to a transformative action that allows tangible applications for design.
The use of biotechnologies makes even more evident the necessity of ethical principles to orient and guide the project. Approaching to biology for the sake of random experimentation involves indeed an array of risks, such as repurposing a future characterised by the same social and ecological issues of today (Ginsberg & Chiesa, 2018).
In nature, any transformation is driven by the concept of evolution; quite the opposite, throughout history humans has pursued the idea of incremental progress, with the negative consequences that we experience in first person today – pollution, climate change, labour exploitation and so on.
Evolution works through adaptation processes, searching for the most efficient solution for survival. It hasn't an individual definite direction, but develops through differentiation according to each specific context. On the other side, progress moves forward, linearly and incrementally, resulting into a growth in some respects but with very few changes, never radical nor disruptive. Moreover, progress is focused on a single point of view, the one of the human being, while evolution acts through a rhizomatic model that encompasses all the living species (Del Gesso & Trebbi, 2019).
Progress is therefore grounded on the absolute idea of "better", striving for the attainment of perfection. Design and Biology however, have a different idea of what "better" means: from the design perspective bettering is related to optimisation and streamlining, while from the biology one means try not to fail (Ginsberg & Church, 2019).
Designers should understand that "better" is not an absolute value but is context dependant: "better never means better for everyone, it always means worse for some" (Atwood, 1985). It is essential to have clear the ethical values on which basing the design activity, and so clarify if the goal is to produce stuff that can be sold on the market – therefore progressing in the model of a capitalist society grounded on GDP which is leading to the planetary ecosystem's destruction – or showing the interconnections between systems and then acquiring an awareness which can push us to reevaluate our attitude towards our surroundings as individuals and as society, evolving as living specie to survive and thrive on this planet in harmony with it.
Ethics is something that is always taught theoretically, and seen more as an obligation than something crucial, while should be taught in more tangible ways that would allow to acquire a concrete awareness on its importance (Lee & Bongaerts, 2019). In this field design can act as ethical filter, visualising through concepts and tangible artifacts the ethical aspects of a technology or project, the possible consequences, and the reactions it may trigger. Besides project developers designers become then interpreter of socio-cultural phenomenons: their activity, beyond the application aspects, is focused also on the communication ones, easing the comprehension of complex topics contributing to overcome fears and closures that often accompany what is new and unknown, as well as pushing to reflection making physically visible the possible consequences of the application of certain processes (Del Gesso & Trebbi, 2019). Through design fiction and speculation is possible to produce the so-called "diegetic prototypes", objects with a strong narrative value which can recount possible worlds – still too far away from collective imagery – resulting from the application of existing processes and technologies.
Designers should therefore be "part of the conversation about how we make sure tech is used for good" (Lee & Bongaerts, 2019), since we are often told only about the best potential of a technology while we should never judge it according to its best use, but rather examine it in the light of all the possible uses, wondering what happens out of sights and behind the scenes (Kaufman & Egender, 2019). Something that should by all means be avoided are projects and experimentations devoid of any usefulness, as in the case of the bioluminescent rabbit by the transgenic "artist" Edoardo Kac, or based once again on the dominance of humans over other species, turned into objects to be exploited to our advantage. A significant example in this respect is the project "Life Support" by R. Cohen e T. V. Balen, where animals as dogs and sheep are used as external organs within life

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5. Biocollectibles - Genetic First Aid Cabinet, part of "Design Fictions: Posthumanity in the age of Synthetics" by Natsai Audrey Chieza: critical design project aimed at provoking debate into the life science industry
6. Bento Lab: portable open source mini laboratory for basic genetic analysis which combines a centrifuge for DNA extraction, a thermocycler to make copies of sequences, and a unit to visualize the DNA and interpret the results
7. DIY CRISPR Cas9 genetic engineering kit for bio-hacking and genome editing sold by Josiah Zayner
8. Artificial Womb, Next Nature Network

support devices for patients with respiratory and kidney disorders. Design can exercise its role of ethical filter developing feasible but also dystopian concepts that display provocative future realities through which raising questions and fostering debates, contributing in this way to the creation of an informed and conscious population able to discuss such topics and make informed decision when necessary.
Designers Hendrik-Jan Grievink and Lisa Mandemaker from Next Nature Studio, have developed a prototype of an Artificial Womb in collaboration with a team of professors and researchers from Máxima Medical Centre in Eindhoven together with scientists from Eindhoven University of Technology. This speculative project was presented at the Dutch Design Week in 2018, and focused on the topic of ectogenesis – gestation outside the uterus –, which is object of a growing debate in which converge issues on feminism, on the role of women and on their control by men as reproductive tool, one of the founding elements of the capitalist patriarchal society we live in.
With biodesign and synthetic biology, intention is now involved in the evolutionary processes, and for this reason it is essential first of all that we adapt to and understand the natural world and life itself before treading uncharted paths, "aware that human intent will not be able to overcome the evolution" (Del Gesso & Trebbi, 2019).

Divulgation & Dissemination

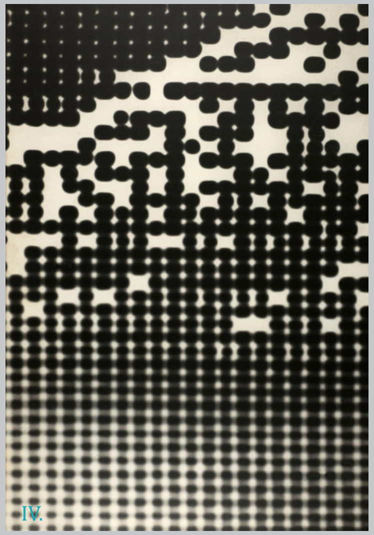
Field Research: Waag Society

The relationship between design and science has always been particularly fruitful resulting in the translation of scientific principles and innovations into tangible artifacts, producing on the other hand an intangible wealth of knowledge. Through this cross-pollination design has the opportunity and at the same time the responsibility to spread and disseminate such knowledge making it easily available for everybody.

One of the first contaminations halfway between art and scientific divulgation was MoMA exhibition in 1936 by Edward Steichen, a photographer with a passion for botany. The exhibition consisted in a range of Delphinium specimens, result of Steichen's twenty-six years of work on cross-breeding and selection, and the plants were exhibited for real rather than through photographs, presenting nature itself as art. Several years later in 1951 Gyorgy Kepes with The New Landscape brings scientific images within the artistic context of an exhibition, highlighting the affinities between visual arts and visualisation of research models. He juxtaposed macro photographs from the science field and works by visual artists, making visible the similarities of patterns, shapes and rhythms.
The Vizzies Visualization Challenge – formerly known as International Science And Engineering Visualization Challenge – is a competition which takes place from 2002 in celebration of the impact that visual communication can have on public understanding of science, organised by the US National Science Foundation in collaboration initially with Science magazine and currently with Popular Science. The competition rewards the ability of researchers, artists and disseminators to promote the comprehension of scientific research results through innovative ways for data visualisation and concept illustration. The collective Syntfarm takes science visualisation to a whole new level with the project Synthazards. Natural catastrophic phenomena such as earthquakes or volcanic eruptions are indeed turned into tridimensional artifacts, expressing the related data through algorithms and translating them into physical objects through digital modelling and fabrication tools.
The XXII Triennale di Milano of 2019, Broken Nature: Design Takes on Human Survival, was all about the relationship between humans and the rest of nature, celebrating design's ability to offer powerful insight into contemporary issues where science, nature, society and design intertwine.

Design has the ability to act as "an agent of change and a source of creative transformation" (Montreal Design Declaration, 2017). It stands "between revolutions and everyday life" (Antonelli, 2008), helping people dealing with change through products and services which influence our behaviour, but also through communication and semantics which are a vehicle for knowledge and socio-cultural values. Design can be a tool to elaborate and decode complex issues, providing a "multifaceted and interconnected framework of the world" without incurring into simplifications


III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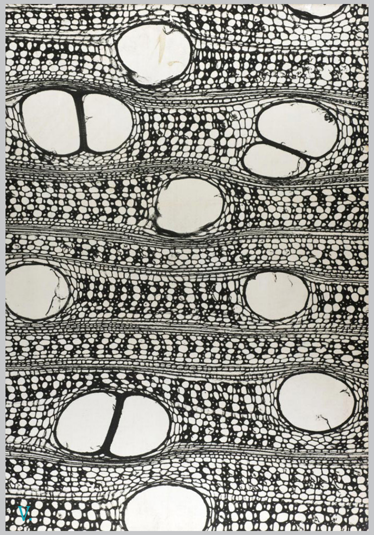
V.

III. Edward Steichen, Delphinums - MoMA 1936
IV. Untitled Date unknown Photographic enlargement on particleboard, date unknown Lent by Department of Special Collections, Stanford University Libraries - Gyorgy Kepes, The New Landscape, 1951
V. Transverse section of wood: 250X 1951 Photographic enlargement, Lent by Department of Special Collections, Stanford University Libraries - Gyorgy Kepes, The New Landscape, 1951

nor homogenisations (Antonelli, 2019).

In the course of this doctoral research, the author spent part of the field research at Waag Society in Amsterdam, Netherlands, a foundation which operates at the intersection of science, technology and the arts, looking at technology as an instrument of social change. Its aim is to help people become active and aware citizens with the aid of emergent technologies, contributing to build a more open, fair and inclusive society through what they call "Public Research". Society then becomes a wide and open research community which allows to drive innovation according to public interest.

Over the last year Waag has been collaborating with Studio Samira Boon, the HybridFormsLab and VU Amsterdam for the project *Labs (Living Aero Bacterial Systems): future interiors*, being involved in particular in the material research and outreach activities as the organisation of three public meet-ups. The project explores the possibility to design interiors as living ecosystems through architectural objects that function in symbiosis with the users, using bacterial cellulose textiles as a substrate for vegetation growth in order to generate airborne bacteria emissions able to enhance indoor air quality.

During her research at Waag Society, the author took part to the first Meetup symposium in a series of three, joining the conversation together with the Biochemist Sandrine d'Haene and the artists Evelina Domnitch & Dmitry Gelfand. The conversation (which had to be moved to an online streaming platform because of the containment measures for the coronavirus pandemic) answered different questions addressing the topic of designing and coexisting with living systems and microbial communities from the different disciplinar perspectives, followed by a question-and-answer session with the public.

Dissemination and divulgation is essential to demystify innovation, especially bio-technological one. People is often biased against the microbial world, associating bacteria to something harmful, a potential contaminant, while they can represent an essential link in the chain of urban and human metabolism.
Ignorance breeds prejudice and fear, and is therefore essential the public involvement into scientific research, bringing it outside laboratories and get it to people even before this happens through products, already since the experimental research stage. Microorganisms may appear disgusting or dangerous to someone, but they can be the keystone for a material revolution which could potentially restore the planetary equilibrium.
This however can't be possible without the participation of a well-informed population, who can move beyond scepticism and actively contribute to the transformative process made possible by biofabrication technologies.


VI.


VII.

VI. Syntfarm, Synthazards, 2009 - earthquake
VII. Beyond Drifting: Imperfectly Known Animals, Mandy Barker - Broken Nature: Design Takes on Human Survival, XXII Triennale di Milano, 2019
VIII. LABS: Future Interiors, Integration of mosses on Kombutex - Studio Samira Boon, 2020


VIII.

3.5. Designing *With* the World

For long time the figure of the designer has been the figure of a single individual, artist or creative, in a strongly individualistic vision of design. Still today for instance, when talking about the key figures of Italian design, we refer to them as the "great masters". Such image however, seems now inadequate in the perspective of design as collective practice rather than autonomous activity.
One of the main things that biofabrication brought to light as a consequence of the interaction with autopoietic living systems, is the loss of the full control of designer over matter, marking the end of demiurgical design and demolishing the obsolete figure of designer as form giver, who acts top-down to shape and linearly control any aspect of the artificial world.
The new perspective that discards designers from their prime position reflects a more general change of vision, which goes from the idea of a "solid" world where individuals are demiurges able to act forcefully and shape it according to their will, to the idea of a "fluid" world where the collective action is the only way to generate change (Manzini, 2018). Reversing the traditional trickle-down approach where the collectivity pretty much passively accepts and adapts to decisions made by others (industry, companies, politics or authorities), is possible to start from initiatives carried out by small groups and communities to affect the large scale of institutions and decision-making, through what Manzini defines "transformative social innovation" (2018).
Today we look at design as a participatory activity grounded on collaboration, starting from the co-design practices which actively involve citizens and users in the design process, up to the new paradigms of biofabrication, where the collaboration extends to other life forms and organisms.
We are aware today that design affects always and however our society and environment, whether this happens consciously or not. Socio-economic human activities are always linked to the Earth system changes, as witnessed by the Earth Overshoot Day[3] which in 2020 was delayed by more than three weeks – from July 31 of 2019[4] to August 22 of 2020 – as a consequence of the worldwide slowdown of most of the human activities during the Coronavirus pandemic lockdown. This gives us the perception of how easy can be bringing about changes on the global scale through a collective action that starts from everyday choices.
Over last decades we shifted from the techno-centric design which put technology before people to the anthropocentric design focused on human and social needs. Today, we are urged to make another paradigm shift and discard the anthropocentric perspective in favour of a life-centric or planet-centric approach to design.
This means to implement cooperation on multiple levels, from ecosystems (in terms of resources and processes), to social systems (in terms of socio-cultural aspects, urban dynamics and the involvement of an active citizenship), up to the micro scale of living systems and the new forms of collaborations with microorganisms implemented by biofabrication. So today we need to understand the fundamental interdependence between each of these levels and shift from designing *the* world to designing *with* the world.

3. The Earth Overshoot Day marks the date when humanity's consumption of the planetary resources reaches the amount which the Earth's ecosystem can renew in a year.

4. In 2019 was recorded the highest level of human footprint on the planet's history until today.

Biofabrication: Research facilities

Biofabrication is a revolution that starts from matter and processes, often carried forward by designers, who open up to science until losing their disciplinary boundaries.
The goal is to create a new matter imagined by humans and fabricated by nature.

Looking at the map indeed, we can see that many research facilities are design driven despite operating in the science field: it is necessary to have the right competences in order to manage biological processes, but the design perspective is essential to envision a future for such processes and technologies, bring them in the real world and identify ethical, coherent and proper applications which could actually generate innovation and change.

Half of the facilities analised is grounded on a transdisciplinary approach merging science and design - to which in the Netherlands is added arts -, the other half operates too in the transdisciplinary field of biofabrication but with a design-driven approach, plus a few examples of science-driven ones. Moreover there is the fablab network (which is of course design based and extends well beyond the few here mentioned), which in many places all over the world is approaching biofabrication combining biological experimentations and wetlabs alongside making and digital fabrication.

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CHAPTER 4 FUTURE FACTORIES

ABSTRACT

With the evolution of design as a discipline, it changes also its relationship with industry, processes and resources. According to the modern idea of design as form, matter, resources and processes were seen as rather marginal elements for designers, even though their activity develops exactly from them. With the growing attention towards environmental issues and resources consumption, designers started to expand their scope to product's life-cycle, although operating within the same system, without questioning it.

In recent years, we witnessed a shift of attention from products to processes, in the awareness that the final product, its shape and features, are indeed nothing but the result of the production process. Design then, ceases to be an exercise in style and embraces the multiple faces of which it is formed. Such a view has brought a brand new relationship with resources and processes grounded on the encompassing of the transitory nature of matter, the understanding of the timing of the planetary ecosystem, and the adaptation to the velocity and cycles duration of its metabolic processes.

This chapter will provide an overview of the level of development and industrialisation of the future materials previously analysed. On one side we will look at the development of networks through which nutrients can circulate from one system to the other, circularising organic and technical waste streams from existing processes. On the other side, we will go trough new forms of post-industrial production, characterised by small-scale vertical urban factories for biofabrication.

4.1. A new relationship with Resources and Processes

4.1.1. Product follows Process

For long time the design history has been read through the perspective of Modern Movement, focusing the attention on the designer more than on the product, and on the idea more than on the mode of production, with an approach based on the individual creativity of the designer (Riccini, 1998). Modernity made matter disappear, subordinating its true nature to a formal will in the pursue of usability or aesthetics, and even if it has remarkably expanded the number of materials available, we lost track of their materiality (Fiorani, 2000).
In such context however, many aspects of the design culture and practice are relegated to secondary roles if not totally discarded, and design assumes a “cosmetic” (Riccini, 1998) and sometimes purely ornamental function.
So true is it that the approach to design as the result of the “creative tension between aesthetics and function” (Collet, 2018), has made that in the relationship with industry design usually comes into play afterwards, intervening only in the last stages of the project development. In this perspective, matter, resources and processes are seen as rather marginal elements for designers, even though their activity develops exactly from them.
In recent years, especially with the advent of biofabrication, we witnessed a shift of attention from products to processes. The final product, its shape and features, are indeed nothing but the result of the production process, and it is therefore necessary to “incorporate design into the process” (Riccini, 1998). Design today ceases to be an exercise in style and embraces the multiple faces of which it is formed. Drawing attention on processes means in fact to draw attention on materials, energy and resources used, from the beginning to the end of the product’s lifecycle.
Looking at design as *form* and designers as form-givers, is the approach which characterised the figure of Industrial Designers, born with the industrial revolution and who put their ability at the service of market, contributing to the construction of a society based on

overproduction and overconsumption, planned obsolescence and seasonality of products. However, the origin of design can be located further back in time – since ancient utensils production – if we look at design as *function*, and so linking it to the technological evolution of humankind. The ongoing shift in perspective which brings us to look at design as *process*, highlights the fact that design can determine the kind of relationship we establish with the Earth habitat, as a result of the close interrelation between technical, social and environmental systems. Artifacts are indeed object of the designer's activity, but at the same time are also intermediaries through which we relate to the outside world, nodes of system networks.
Today we are embracing a pluralistic vision which puts together different perspectives as sides of the same coin, a vision that is not intended to replace the previous ones, but to add to them new tiles, finding a synthesis that can give back the complexity which every artefact bears in itself, as twist of semantic, perceptual, cultural, functional, economic, productive and environmental aspects.

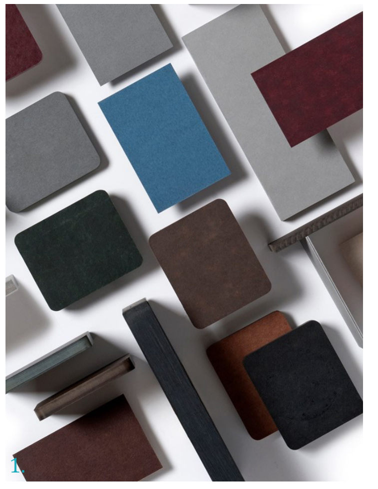
4.1.2. Transformation of Matter and Energy

The pre-industrial era was characterised by a quite balanced resources consumption, especially because of the slowness of production rhythms. With industrialisation instead, we witnessed the rapid acceleration of productive activities, followed by the massive mining and exploitation of the natural resources available. Modernity has been first the age of iron and carbon and later of steel, up to plastics and synthetic polymers emblem of contemporary age. Materials were therefore extracted from Earth, moreover they represented a "solid-fluid matter" (Fiorani, 2000), which can assume a wide variety of forms – characterised by smooth surfaces and perfect geometric shapes –, and can be shaped at will by humans in an infinite and controlled transformation.
With the industrial revolution and mass production is spread a concept of cheapness of material and production, oblivious of the global cheapness and therefore the environmental impact. The industrial system of last centuries indeed, is based on a model according to which the material is cheap while shape, and then the production process, is expensive, overturning the laws of nature which state the exact opposite: shape is cheap while material is expensive because a lot of metabolic energy is needed both to assemble and to disassemble it (Benyus, 1997). Natural organisms tend to use less matter distributed in the most efficient way, through controlled anisotropies and specialising each point as necessary (Manzini, 1986).
With the Kyoto protocol of 1997 emerges the concept of limit and the idea of development in a limited world. The awareness that the planetary resources are anything but inexhaustible begins to spread, and design moves towards recycle and life cycle assessments, without however discarding nor questioning the existing industrial development model.
In the last few years a new way of looking at materials and resources is spreading within the design community, searching for alternative abundance within the large amount of waste streams of current production systems, and circularity with organic and living materials.
As part of nature, we need to learn from it and understand how to replicate the equilibrium condition of natural systems where "the fruit already contains in itself the seed through which it can self-recycle and produce more identical fruits" (Munari, 1991). We need to encompass the transformative processes of matter, abandon the illusion of permanence and embrace the transitory and cyclical nature of everything existing, as well as the idea of death (Agapakis, Solanki & Montalti, 2020). Quoting J. Vincent, J. Thackara remembers us that "We would not be here had not our ancestors rotted" since "all organisms are designed with the intention of being recycled" (2005). In the world of biofabrication microorganisms do nothing but transform given substances into new matter, but if we look at non biodegradable materials we can see that they die and transform anyway but in way much longer timeframes – it just happens on a time scale far from our perception.
Plastics for instance, took millions of years to form and require from a hundred to a thousand years to degrade. If we consider that they are employed mainly for products with short or almost nil usage time, the only possible consequence is the accumulation of mountains of waste (without considering the additional release of toxic substances into the environment during manufacture and disposal).
Modernity has favoured the present instant in a conception of time which is abstract and mechanic. The key-machine of modernity is the clock, a tool which enables us to domesticate time (Fiorani, 2000). To move past such anachronistic illusion of control over the passing of time we need to understand the timing of the planet ecosystem, and adapt to the velocity and cycles duration of its metabolic processes choosing the right material for the right product, which means to use ephemeral biodegradable materials for products with a shorter lifespan, and durable materials for durable applications.

4.2. Waste streams

Since we act within interconnected open systems, we need to understand and re-design the nutrient flows among them, connecting different production realities in order to foster the creation of networks through which nutrients can circulate from one system to the other.
Agro-industrial waste is already used for the production of many materials. As we have seen in chapter two, the typologies of waste available are many, both organic and not. Many producers are using them to search for ethical and non impactful alternatives to animal leather. The best-known is *Piñatex*, a textile made from cellulose fibres extracted from pineapple leaves, which are however mixed with PLA and petroleum-based resins. The same happens with *Pellemela* by Frumat, a leather-like material made from apples waste resulting from the fruit's industrial transformation in northern Italy, which is mixed at fifty percent with polyurethane. Both materials have already been implemented into products available on the market such as shoes and bags, but in no way they represent a valuable alternative to traditional leather, since they are a clear example of "monstruous hybrids" (Braungart & McDonough, 2002). *Wine leather* is instead a hundred percent vegetable-based, and it is made from fibres extracted from grape's peels and seeds found in pomace – wine production leftover. It is produced by the company Vegea in Italy, where there is a large wine production and therefore access to large amounts of pomace. *Fruit Leather Rotterdam* is a Dutch company which has been experimenting on how to convert left-over fruit into leather-like material, using discarded fruit from Rotterdam's markets that can't be sold anymore, creating in this way a link between fruit industry and textile industry. Fruit waste is also used by the Danish company *Beyond Leather*, which produces vegetable-based leather using apple pulp mixed with a thirty percent of plastic-free additives. In México instead, the company *Desserto* uses cactus as raw material for vegetable leather production, harvesting the mature leaves or cladodes from organic cactus plantations, and using just sunlight energy to dry the raw matter.
Remaining in the textile field, the Italian company *Orange Fiber* has patented a new textile made from citrus fruits' peels, connecting even in this case the food industry with the fashion and textile one, using agricultural byproducts as source for cellulose-based yarn production and then weaving it into textiles. Organic agro-industrial waste is used also in the making of other material typologies such as paper, as in the case of *Cartamela* – from Frumat, the same company producing Pellemela – where apple peels are turned into toilet paper, napkins etc., or G. F. Smith which besides traditional paper is producing samples from different kinds of waste as beer spent grain, using the features of different beers – lager, pils and ale – to create a colour palette. The company 3M instead, produces a kitchen sponge – example of a common everyday object with a short lifespan, usually made of polyester or polyurethane – using agave fibers from tequila production.
Besides organic waste we have also technical nutrients flows, made of inorganic waste from manufacturing processes. The Amsterdam-based start-up *StoneCycing* for instance, has developed a range of twenty recipes to create waste-based bricks of different colours, made from rejected clay from traditional bricks manufacturing as well as waste from glass and ceramic industries. The designer Mieke Meijer has been working with urban waste, and developed a new material called NewspaperWood using old newspapers reversing the traditional production process, and so going from paper to wood instead that from wood to paper.
Recycled paper[1] itself has found many applications in the production of new materials. *Re-y-stone* is a resistant material used for wall covering and laminates, made combining recycled paper fibers with a bio-resin obtained from bagasse – byproduct of sugarcane manufacturing. *Paperforms* instead is made from a hundred percent waste paper, turned into panels used for surface coverings with different properties as sound absorption. *Paperstone* is made using recycled paper and cardboard impregnated with an organic resin extracted from cashew shells and coloured with natural pigments. The material has great technical-performative features such as water and fire resistance and is used for furniture production.
There are many other examples of paper-based materials, but in some cases the paper pulp or fibers are mixed with fossil-based matter, falling here as well in the category of "monstruous hybrids" (Braungart & McDonough, 2002). It is the case of *Richlite*, rigid panel of "solid paper" made from layers of recycled paper and phenolic resin, used, among others, in the making of guitar fretboards

1. Paper recycling is actually subcycling, a process which entails the reduction of the material quality over time. Indeed for the production of recycled paper a certain amount of virgin cellulose fibers is always needed, since the recycling process provides for the breaking of the bonds between the cellulose fibers, making them shorter and shorter until they are too weak to be used for paper production



1. Paperstone samples
2. Paperstone sink and kitchen furniture


3.


4.


5.

3. Desserto Leather
4. StoneCycling waste-based bricks
5. NewspaperWood
6. Orange Fiber by Adriana Santanocito & Enrica Arena

in place of wood. This means that different kinds of "technical nutrients" are mixed together with no possibility to retrieve neither of them to be reinserted in material flows, therefore not fulfilling the requirements of circularity.


6.

4.3. Living Factories

The functioning of biofabrication processes is giving us the opportunity to envision and implement new forms of post-industrial production characterised by small scale urban factories, local resources flows, diffused production and decentralisation.
The phenomena which Maffei & Bianchini defined "distributed microproduction" (2013) is something which already started to spread in the design field with the Makers and DIY culture. New craft practices and digital manufacturing technologies indeed, allowed designers to start a journey of democratisation and re-appropriation of the means of production. Distributed microproduction lays the foundation for radical changes in the production system affecting both manufacturing and distribution, fostering "the creation of alliances, communities and movements by modifying existing power relations" (Maffei & Bianchini, 2013).
Growing materials as mycelium, yeasts or microbial cellulose don't require bulky equipment and can be grown in layers, which enables their production in smaller spaces that can develop vertically rather than horizontally, as is the case of shelving for bakeries or hydroponic agriculture. Moreover they don't require sunlight energy and can therefore be placed indoor, in any place where is possible to control environmental parameters such as temperature or humidity rate. Is then possible to place such production facilities within the urban fabric, as opposed to the industrial model where the manufacturing sector is relegated to large suburban areas, with all the resulting social consequences in terms of housing, "commuter towns" and neglect. This is due to the huge size of industrial production structures, but especially to the negative environmental impact caused by polluting discharges and emissions, that are kept far from the eyes – and lungs – of the city dwellers, to the detriment of the inhabitants of such suburbs.
Grounding our future production system on biological processes, in respect of both people and environment, means to carry out a radical systemic innovation encompassing the technological, social and environmental sphere. We need then a total change of frame which

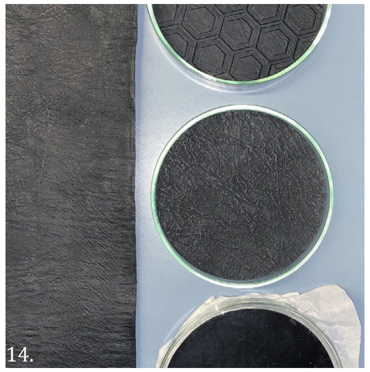
7-8. Mycelium Factory - Ecovative Design, New York
9. Brewing Rack - ScobyTec, Leipzig, DE

would allow us to do what we currently don't, without pursuing any improvement within the current frame, which would only lead to incremental innovation, in continuity with what we have been doing until now (Norman & Verganti, 2014).
This necessarily requires "co-operation between and across organisations and sectors", and can be put into effect only "when a number of complementary innovations occur in a parallel and interconnected way", certainly not by a single organisation or individual (EU report, 2012). Systemic changes indeed, aren't the consequence of Incremental changes, but of the accumulation of radical changes on the small scale.
As mentioned in the previous chapter, the biofabrication revolution is following this pattern, being led by multiple independent small firms rather that few major companies. It is developing through horizontal scaling, linking different production systems – food, agriculture, materials, textiles, etc. – according to ecosystemic logics, therefore drawing from the local resources available in different geo-climatic regions in order to repurpose them locally, eliminating the impact of large-scale distribution in terms of logistics and worldwide transportation.
Making the new biofabricated materials available to people depends on scalability and costs, materials' performances and appreciation by users. Currently this path has just begun and we will probably be able to see the result of this process not in five but rather in fifty years, a time when our productive systems could be totally revolutionised affecting everyone's life globally, but in order to reach this goal is essential to start right now. In such early stage however, there are several companies and start-ups which have taken their researches to advanced levels of industrialisation.
In the realm of algae, there are companies as *Spira* and *Living Ink* which are using it for colouring purposes, in the first case for food applications while in the second case for the production of environmentally safe inks for packaging and textiles. *Algiknit* instead, has created a biodegradable yarn made from polymers extracted from seaweed such as kelp, employed in textile production to address the issue of synthetic fibres in the fashion industry.
The most advanced sector is probably the one of fungi, with the industrial development of different material typologies made from mycelium or yeasts. One of the first companies founded in this sector is *Ecovative*, which started producing mycelium composites to substitute plastic packaging and has now developed a second generation of materials called *Mycoflex* made of pure mycelium foam, which can be used for textiles production but also as a scaffold for cell growth for food applications as their *Altlast* lab-grown meat. The start-up *MycoWorks* instead, in February 2020 has launched *Reishi* at the New York Fashion Week, a mycelium textile obtained forcing the mycelium cells into a woven structure during the growth, giving it high strength and durability.
Mogu is employing mycelium to create products for interior design, such as acoustic panels made of fungal mycelium and upcycled textile residues, or flooring realised with a mycelium composite core coated with a 95% bio-based resin. The company, in collaboration with Officina Corpuscoli, is now working on *Pura Rucksack*, made of mycelium textile. Also *Mylo Unleather* by *Bolt Threads* is a new kind of mycelium textile, which thanks to the collaboration with brands like adidas or Stella McCartney should be implemented in fashion products available on the market starting in 2021.
Remaining in the realm of fungi, Bolt Threads has developed a biofabricated version of spider silk thanks to bioengineered yeasts, used to produce the "Biofabric Tennis Dress" by Adidas & Stella McCartney. The company *Modern Meadow* is producing the lab-grown leather Zoa from yeast cells, engineered to produce collagen proteins through fermentation. Yeast fermentation is used also by the company *Spiber* to fabricate spider silk proteins then turned into a yarn. The company started a collaboration with North Face to develop a spider silk version of their Moon Parka, currently still a prototype.
Fermentation processes and yeasts are used in collaboration with bacteria for nanocellulose production. The start-up *ScobyTec* is producing microbial cellulose for applications in the textile and automotive industry, while *MakeGrowLab* is using it for packaging applications. *Malai* harness the bacterial fermentation to produce nanocellulose from wastewater of the coconut industry; the nanocellulose is then processed to create a biocomposite waterproof textile used for bags and other fashion products. The company *BioMason* instead, produces a biocement for construction purposes using bacteria to grow bricks through microbial induced calcite precipitation, reducing both energy use and carbon emissions compared to traditional cement. We saw how bacteria can be precious collaborators also for dyes production. In 2020 Puma, in collaboration with Living Colour and Streamateria, has realised the sportswear collection *Design to Fade*, exploring how we can re-think the fashion industry through biofabrication.

10. Mycoflex - Ecovative Design
11. Microbial cellulose biocomposite shoes - Malai Biomaterials
12. Mylo Unleather - Bolt Threads

13. Algae yarn, Algiknit, NY
14. Black Bacterial Nanocellulose Samples, with natural grain or embossed - ScobyTec, Leipzig, DE
15. Puma x Living Colour - Design to Fade

13.



14.

15.

Some of the products of the collection are coloured with bacterial dyes, while others are made of degradable materials characterised by closed loops cycles and manufactured locally.
Despite grounded on biological and biotechnological processes, many of the leading companies in the biofabrication world mentioned above – Algiknit, MycoWorks, Mogu, Modern Meadow, BioMason – have been founded by designers, underlining the strong design component of such material revolution. By the way, all of them are grounded on transdisciplinary collaboration between science and design, essential to properly face the paradigm shift of biofabrication, mastering the processes on which it is based without losing the systemic perspective which intersect technical matters with social and environmental ones.

scaling up: Mogu

case study

Officina Corpuscoli is a transdisciplinary design research practice based in Amsterdam founded by Maurizio Montalti in 2010. It is also the incubator which gave birth to Mogu, design company producing mycelium-based products, founded in 2015 in Inarzo, Italy.
Within the context of Officina Corpuscoli, operating in the hybrid field between design and science, the investigation is on a more speculative level, the research and design activity follows a creative and explorative approach, and the designer has broad freedom and scope.
In the context of Mogu instead, the practical aspects related to the achievement of the technical level required for industrialisation come prior to others. The company was born from the desire to reach a wider target, not addressing just a small minority of biodesign and biofabrication enthusiasts or a cultural elite, but soaking into everyday life to trigger real change.
The main goal then, is to standardise mycelium biofabrication processes and products in order to make them suitable for industrial development. This requires facilities to conduct proper techno-scientific analysis as well as team diversity, and therefore the partnership with diverse professionals who can provide all the needed skills to sustain the company – biologists and biotechnologists, chemists and material scientists, marketers and business developers, product and communication designers.
The company is currently producing acoustic wall panels made with mycelium and textile waste, and floor tiles made with mycelium composites and 90% bio-based resins. The tiles are produced in different colours, obtained employing organic waste such as rice straw, seaweed etc., valorising waste and byproducts of agro-industrial regional industry.
Mogu has also a biotech division, which is technology-oriented rather than product-oriented: Pura, a biofabrication lab aimed at the development of advanced processes based on fungal fermentation for both the fashion and the food industry.

The main challenges to face when shifting from the research to the market dimension include the ability to combine the visionary view of designers with the need to validate the idea within a market, together with succeeding in finding the right balance between the standardisation of industrial processes and the uniqueness of biological ones, at a level which ensures compliance with the regulations that govern product certification.
The MOGU experience therefore, teaches us that designers needs to adjust their expectations in order to be able to produce products that can actually be sold and accepted in the market (Lucibello & Montalti, 2020). To scale up and move from the more explorative phase of design research – where the focus is on cultural and communicative aspects – to the more concrete industrial dimension – which has to meet specific performance and market requirements –, we have to deal with several constraints and be able to find the balance point among all the systems – economic, natural, microbial, social, cultural – which intersect in the biofabricated design project.

I. Mycelium composites
II. Pura Rucksack prototype
III. Acoustic panels

Biofabrication & Biomaterials Companies

United States

AlgiKnit - Brooklyn, New York

BioMason - Research Triangle Park, NC

Ecovative Design - Green Island, New York

Ginkgo Bioworks - Boston, MA

Living Ink - Aurora, CO

Modern Meadow - Nutley, NJ

MycoWorks - San Francisco, CA

Mylo Unleather - Bolt Threads - Emeryville, CA

Spira inc - Los Angeles, CA

Mexico

Desserto leather - Guadalajara, MX

Europe

Beyond Leather - Rotterdam, NL

Bio Faber - Mesagne (BR) IT

Caracara Collective - Helsinki, FI

Fruit Leather - Rotterdam, NL

Grown Bio - Hilversum/Hedel, NL

MakeGrowLab - Puławy, PL

Mogu - Inarzo (VA) IT

Orange fiber - Catania, IT

Pinatex - London, UK

Frumat - Bolzano, IT

ScobyTec - Leipzig, DE

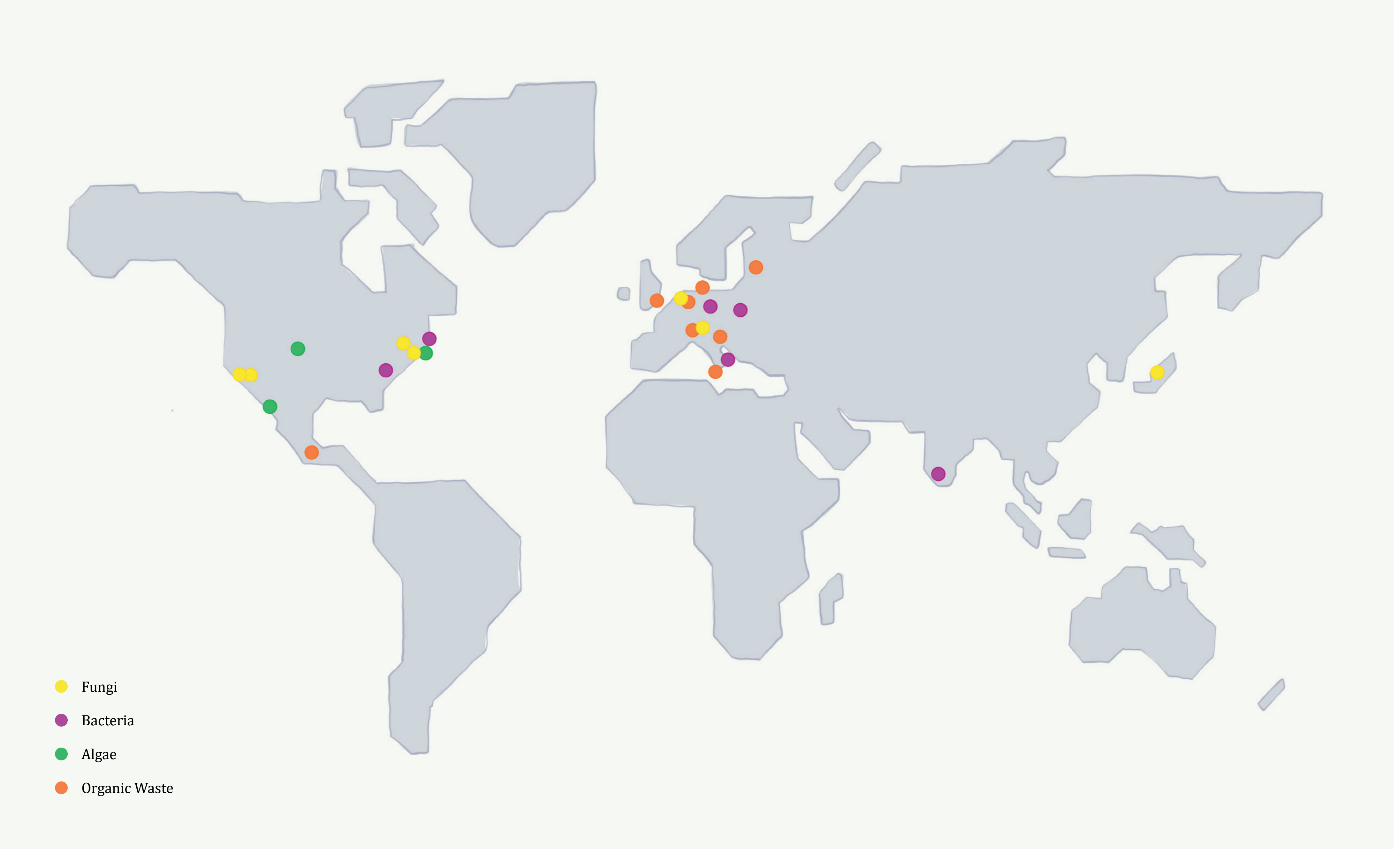
Vegea - Milano, IT

India

Malai - Cherthala & Fort Kochi, Kerala, India

Japan

Spiber - Yamagata, JPN



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PART II

Hands-On

No action without research,
no research without action

Kurt Lewin

CHAPTER 5

HOW TO DESIGN WITH NATURE

ABSTRACT
The first stage of experimentation consisted in a set of hands-on basic experiments on biomaterials, aimed at providing an exhaustive panorama of possibilities and acquiring a clear overview of the main materials and processes in the field of biofabrication and biodesign. To explore materials through first-hand experience means to understand their behaviour, properties and personality, and to be able to implement them into products which can valorise and enhance such features.
In order to design with nature we need to understand its laws and learn how to manage its processes. We are interacting with a new matter and with processes hitherto unknown to design. We need then to fill the knowledge gap on this topic and develop the basic skills needed to deal with the world of "future materials". This approach wants to emphasise the central role of experience, first-hand experimentation and craft activity within design research. Experience indeed, according to learning-by-doing and experiential learning theories, represents an essential learning tool. Experience is a process, always related to the context and therefore result of specific situations, enabling us to confer a concrete dimension to theoretical research.
The methodology developed is grounded on the principles of Action Research, through which creating a synthesis between theoretical and practical dimension, reflection and action. It involves the alternation of experimental phases and sensory exploration phases, essential tool for analysis and information gathering. The succession of each phase should not be understood as linear process, but as circular iterative process entailing the repetition of some phases according to the results of the previous ones, tracing an ever-changing path determined from time to time by the variables involved.
With the overcoming of disciplinary boundaries and the consequent hybridisation between design and science, design methodologies are shifting towards the systematic and documented study which characterises the scientific method. Acquiring methods and approaches from science is essential to face the world of biofabrication. However, this doesn't mean to substitute them to the ones of design, but rather hybridise them through cross-contamination of tools and methods: provide meaningful analysis through the acquisition of measurable data, while still keeping the designer's synthetic-inductive perspective.

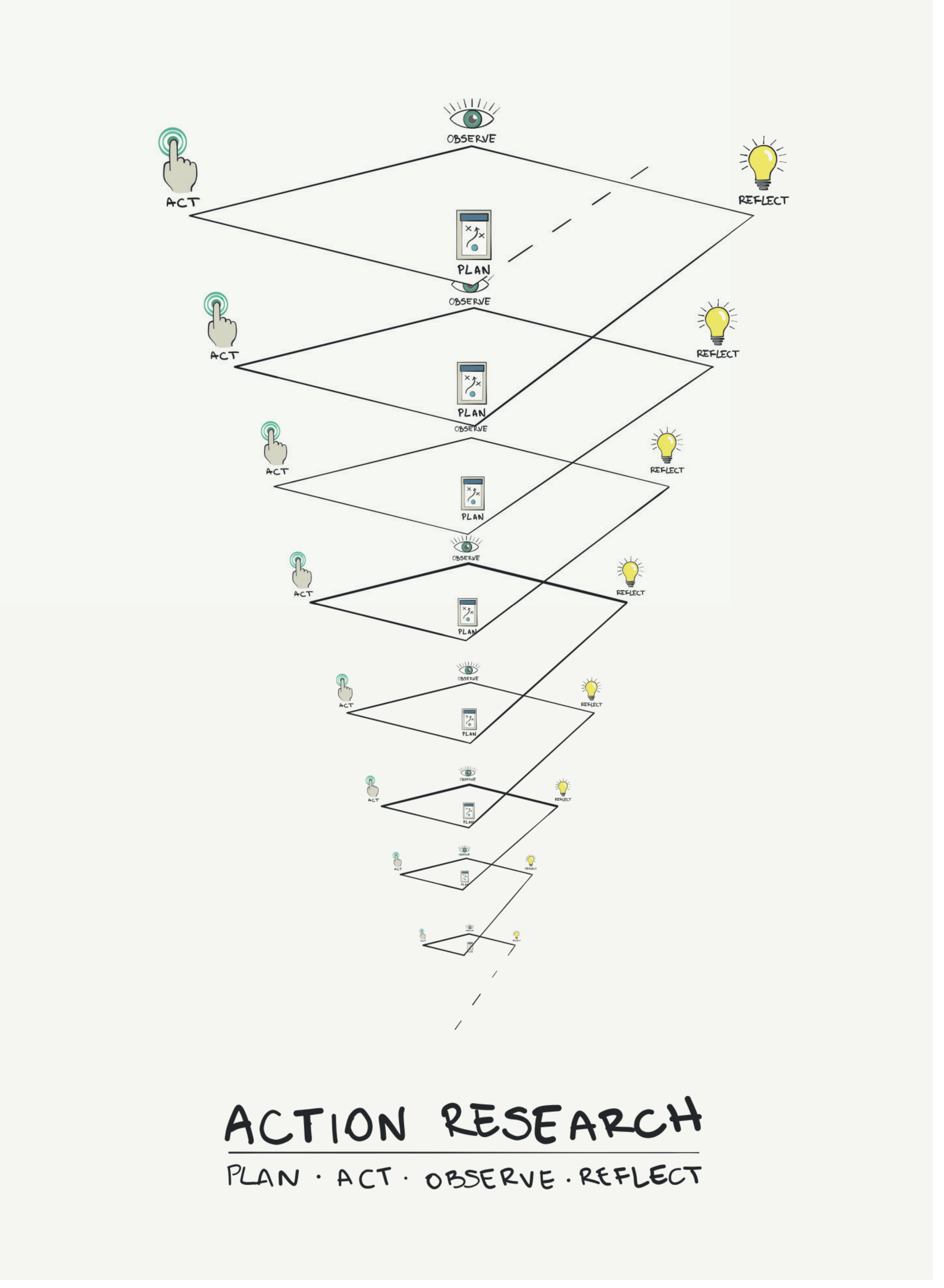
5.1. Material Experiments

The field research of this doctoral thesis was developed around material experimentation and the first stage consisted in a diverse set of hands-on basic experiments on biomaterials. The goal was to acquire a clear overview of the main materials in the field of biodesign and biofabrication. Knowing bio-materials through first-hand experience rather than analytically means indeed to understand them, their behaviour, features and personality, and therefore to be able to use and implement them into projects and suitable applications which could enhance their specificities without distorting their identity.
The basic experimentation develops then horizontally, in order to provide an exhaustive panorama of possibilities and discover the potential of new bio-based and bio-fabricated materials. This stage is propaedeutic to the following part of the material experimentation described in chapter six, which will continue with an in-depth "vertical" exploration of one of the materials object of the basic experimentation.

5.1.1. Experience, Action, Reflection

To design with nature we need to understand its laws and learn how to manage its processes, which have always been subject matter of science and its branches, from chemistry to physics to biology. Within such hybrid dimension in between design and science, designers' primary need is to fill the knowledge gap on this topic. We are indeed interacting with a new matter, and with processes hitherto unknown to design. We have then to learn how to approach the new laboratory dimension of the project, how to co-create with living matter and develop all the basic skills necessary to deal with the world of future materials.
Skills can be developed and acquired only through experience. They are "a way of dealing with things, not a derivation from theory", they can be improved by theory but only when theoretical knowledge is translated into habits (Bruner, 1997). Experience is therefore an

essential learning tool, as claimed by Dewey with the learning by doing approach and Kolb's experiential learning theory. Learning by doing is the learning model notoriously adopted by the Bauhaus, defined as an active elaboration of ideas which locates in the experience the starting point for knowledge building, opposed to the passive kind of education based on superficial factual knowledge (Dewey, 1938). When talking about experience Dewey defines it a process, and upholds the principle of continuity of experience according to which "every experience both takes up something from those which have gone before and modifies in some way the quality of those which come after" (1938). Moreover for Dewey experience is strongly determined by the environment, and then by the people with whom we interact, the subject of the conversation we carry on and the materials of the experiments we perform. The environment includes "whatever conditions interact with personal needs, desires, purposes, and capacities to create the experience which is had" (Dewey, 1938), which means experience is the result of the specific situations in which interactions take place.
According to experiential learning theory, the learning process is a four-stage cycle consisting of: concrete experience, observation and reflection, formation of abstract concepts, testing implications of concepts in new simulations (namely start from hypotheses to create new experiences). The learner will therefore need "four different abilities – concrete experience skills, reflective observation skills, abstract conceptualization skills, and active experimentation skills" (Fry & Kolb, 1979). Kolb describes experiential learning as something that goes far beyond didactics, defining it the "central process of human adaptation to the social and physical environment", an holistic process involving "the integrated functioning of the total organism – thinking, feeling, perceiving, and behaving" (1984).
This research wants to emphasise the central role of experience, first-hand experimentation and craft within design research, especially when approaching biofabrication and material development. The hands-on experiments represent the means by which building the needed knowledge, since craft and manual activity represent "a dynamic process of learning and understanding through material experience" (Gray and Burnett, 2009).
Besides describing experience as a process, Dewey defines it also a "moving force" (1938). The experiential dimension indeed, allows designers to actively interact with materials and processes, technologies and products, instead of just being passive learners or users, becoming then an essential tool for research especially if aimed at triggering change.



Design can create a synthesis between the theoretical and practical dimension, reflection and action. Within design research artifacts and processes behind them become the "target of the reflection" (Nimkulrat, 2012) and at the same time its source: research is both "reflection in action" and "reflection on action" (Schon, 1983). This principle is at the base of Action Research, a research methodology in the social science field, now assimilated in the design practice.
Action research was first conceptualised by Lewin in 1952, who stated that there is "no action without research, no research without action". It develops through "a spiral of cycles of action and research consisting of four major moments: plan, act, observe, and reflect" (Zuber-Skerritt, 1992).
Lewin emphasised the importance of here-and-now concrete experience as the way to validate and test abstract concepts (Kolb, 1984). Action research methodology is based indeed on feedbacks, and develops as a continuous process of goal directed action followed by consequences evaluation. It must therefore necessarily involve experiments, "which serve to generate both a new understanding of the phenomena and the change in the situation" (Schon, 1983). Through experiments researchers can obtain unintended results which can produce new meanings, and then, through feedbacks and observation, they can reframe the experiment from time to time in an iterative cyclical process.
According to Swann action research methodology requires three conditions: "First, its subject matter normally is situated in a social practice that needs to be changed; second, it is a participatory activity where the researchers work in equitable collaboration; and third, the project proceeds through a spiral of cycles of planning, acting, observing, and reflecting in a systematic and documented study" (2002). According with this definition action research and design activity appear very close: design is an agent of change, deals with social practices and follows an iterative cyclical process which goes from analysis to synthesis. Such closeness seems to decrease if we look at the second and third conditions about participation and systematic reflection. However some steps in this direction are already being made with transdisciplinary research, active citizenship, co-design practices, and all forms of participation and collaboration – with people but also with nature and living organisms –, in the growing awareness that designers can't work as solo practitioners anymore. Moreover, the overcoming of disciplinary boundaries and the consequent hybridisation of methods between design and science is bringing design methodologies towards the systematic and documented study which characterises the scientific method.

5.1.2. Basic experiments: Methodology

The Basic Experiments described in this chapter have been useful to establish a protocol and build a methodology in order to approach the biofabrication scenario and the laboratory dimension from the design perspective.
According to Cross (1989), the main methodological difference between science and design is that science problem-solve by analysis through problem-focused strategies, while design problem-solve by synthesis through solution-focused strategies. Scientists then "look for underlying rules which would enable them to generate the correct, or optimum, solution", on the other hand designers "suggest a variety of possible solutions" until they find one that is satisfactory (Cross, 1989).
Within the framework of experimentation we need then to acquire methods and approaches from science without, however, substituting them to the ones of design, but rather hybridising them through cross-contamination of tools and methods. This will allow us to do a systematic data collection and provide meaningful analysis while still keeping the design's holistic perspective and its ability to envision, synthesise and translate the result of the experiments into tangible products and real-life applications.
It is then necessary to establish precise steps and defined protocols as happens for science investigation, but to address them with a design-driven approach: guided by induction, creativity and invention. In this way what is an error from the scientists' perspective can become a new discovery for designers and lead to unexplored paths. Designers' approach will be focused on perception, aesthetics and semantics despite maintaining scientific rigour in the experimentation, which will allow us to control and reproduce processes, but especially to acquire measurable data through which gaining an understanding of processes and of the matter in question.
The experimentation was so structured in different steps, identifying some pivotal moments. However this doesn't mean to follow a linear univocal process, but rather a circular one based on feedbacks, with a continuous reworking of the steps to follow according to results and observations emerging from each stage that can often determine changes of direction, tracing a path which from time to time is determined by the variables involved.

1 · REMAKE

Information gathering from existing protocols and basic recipes reproduction

2 · TINKER

First moment of observation and manipulation of the material sample. Data collection through senses in order to imagine the potential of the material and set up the first experiments

3 · EXPERIMENT

Inductive experimentation which starts from processes.
When approaching a new material this is a useful stage to gain an understanding of its behaviour and characteristics. Intervene on one or more variables individually by trial and error implementing large variations to explore the effects in a broad spectrum. This will allow to understand the relationship between material and process, and therefore how the material's features can change according to the process' components or variables.
The more the input data and the prior knowledge are extensive the more this stage gets closer to a targeted experiment

4 · SENSE

Experiential analysis of the results, again based on tinkering and sensory exploration, through which identify what works and what doesn't in order to recalibrate the experimentation narrowing the scope of investigation

5 · FOCUS

Focused experimentation which starts from material's features.
Following a rigorous approach realise material gradients through slight variations in the process, according to specific features identified in the previous stage on which to intervene. It is essential to act on one piece at a time separately so as to obtain measurable and significant results, and consciously interact with the process to produce material palettes which cover the range of possibilities for each of the feature (from rigid to flexible, from opaque to translucent, from thin to thick, etc.)

6 · ENVISION

Material as input for concept development.
Tinker, observe, test and stress the samples realised. The direct interaction with the material makes us grasp its personality, its qualities and defects, identify its strengths and from them draw inspiration to imagine the possible applications, finding among the several samples produced the right material for the right application

7 · FABRICATE

Targeted experiment for design prototype fabrication.
Select and implement a specific process among the ones carried out previously in order to get specific material features weather they perceptual – colour, texture, opacity, smell, etc. – or performative – resistance, porosity, flexibility, etc. – according to the product that is going to be realised

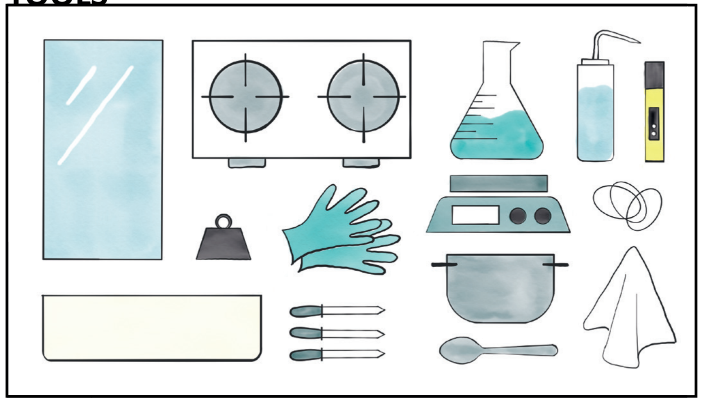
As mentioned above, the experimentation doesn't have to follow linearly these steps but will probably require some iterations of the intermediate stages from 3 to 6 involving the general experiments or the focused experiments, or both.
The basic experiments collected here, generally reach the intermediate stages of the methodology described, while in the following chapter the methodology is applied to the second phase of the material experimentation with the Advanced Experiments. This phase will consist in the selection of one of the materials explored within the basic experiments, and a deeper investigation which will lead to the development of proper application scenarios.

5.2. Exploring the evolving matter: basic experiments

5.2.1. Bacteria: S.C.O.B.Y.

Bacterial nanocellulose is the byproduct of the fermentation process of a symbiotic culture of bacteria and yeasts or scoby. During the process the yeasts ferment sugar turning it into ethanol, which is in its turn converted into organic acids by bacteria (as Acetobacter or Gluconaceobacter). As a result of such process nanocellulose fibrils are spun in the culture container and are stratified on the surface of the growing medium and join together creating a unique layer. In order to grow, the culture requires an acidic environment with a pH between 2.5 and 3.5, oxygen since it is an aerobic process, and a temperature between 20-30° C.

TOOLS



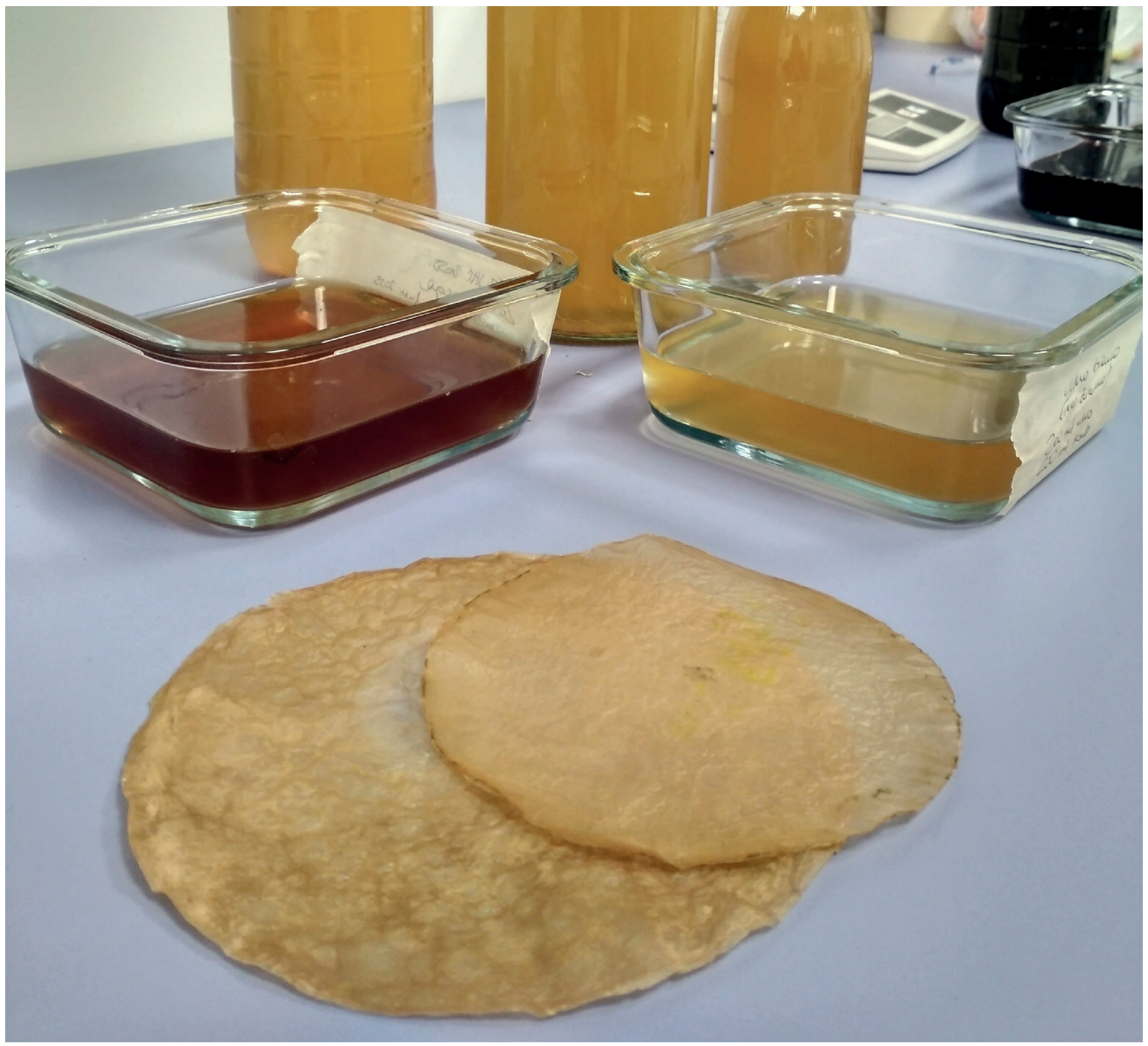
DRYING PANEL
STOVE
BEAKER
ETHANOL
PH-METER
WEIGHT
GLOVES
SCALE
RUBBER BANDS
CONTAINER
PIPETTES
POT
SPOON
CLOTH/LID

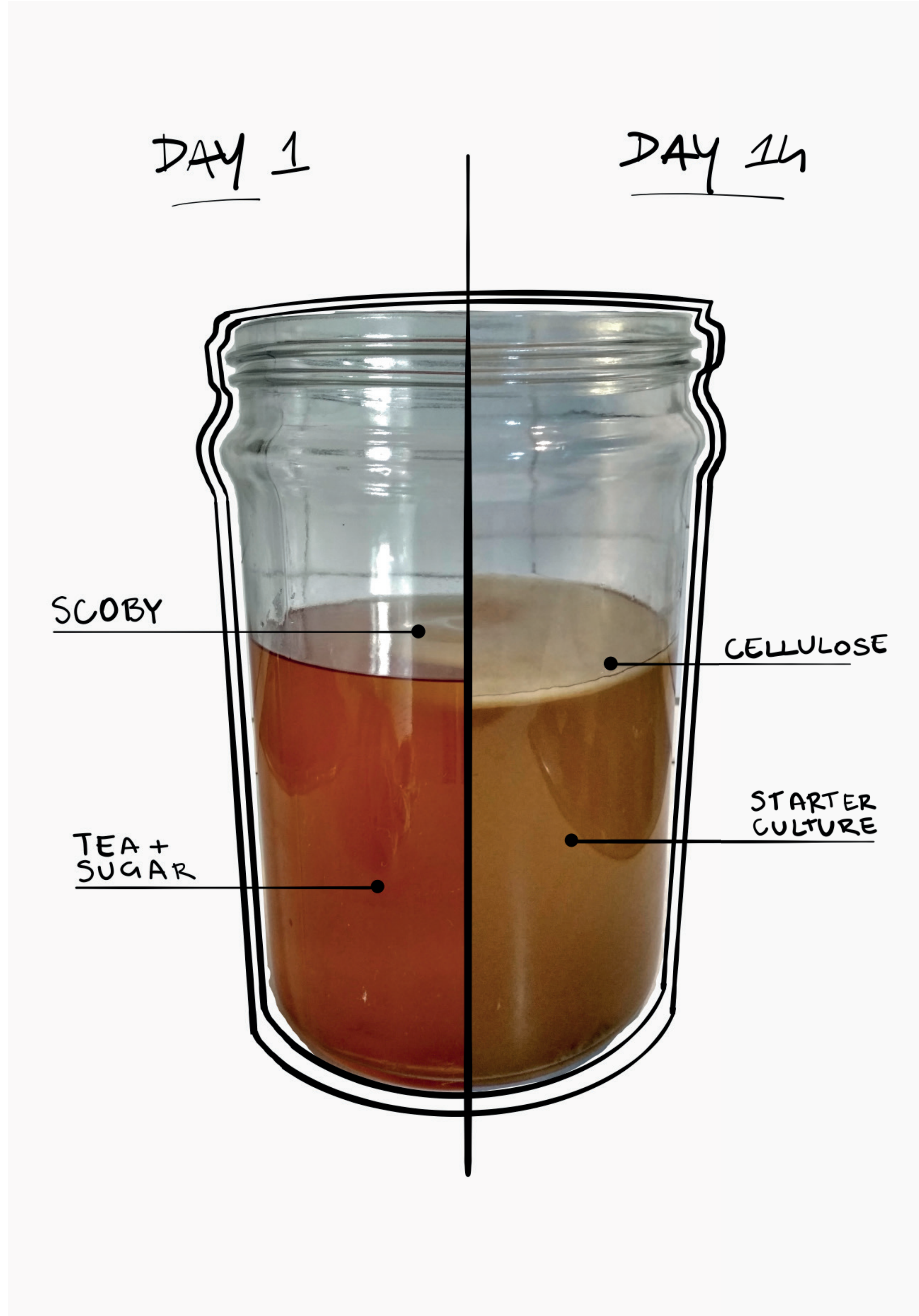
INGREDIENTS

PROCESS

- Wear gloves and sterilise all the containers and instrument used to prevent contamination
- Boil the water, add the sugar and stir, then add the teabags and leave to rest
- Wait until the water cools and reaches room temperature, measure the pH and gradually add vinegar to reach the right acidity
- Add the scoby, use the weight to keep it on the bottom of the container
- Cover the container with a breathable cloth or a lid
- Keep in a dark ventilated environment without moving the container
- When reached the desired thickness harvest the material from the surface, wash it with neutral soap and rinse with water
- Place it on a flat surface for drying (different surfaces will result in different surface textures), remove all the air bubbles, turn it periodically on both sides until dry

* the remaining liquid can be used as starter for a new culture, it is already acid so ther is no need to add vinegar, and can be feed with new sugars to continue the fermentation process again and again

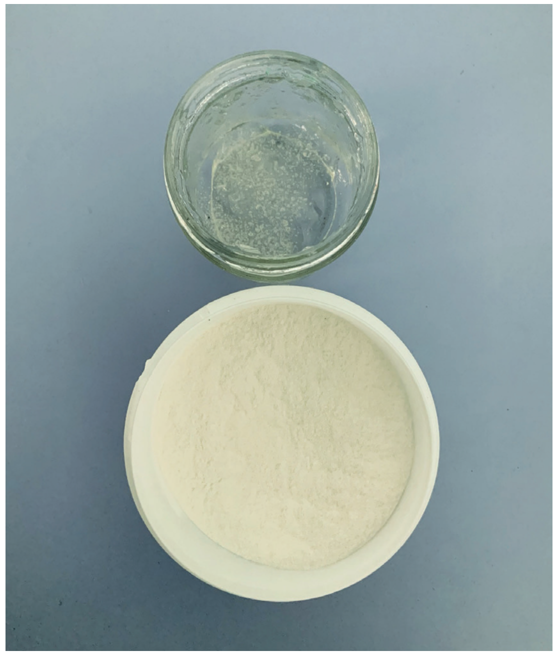




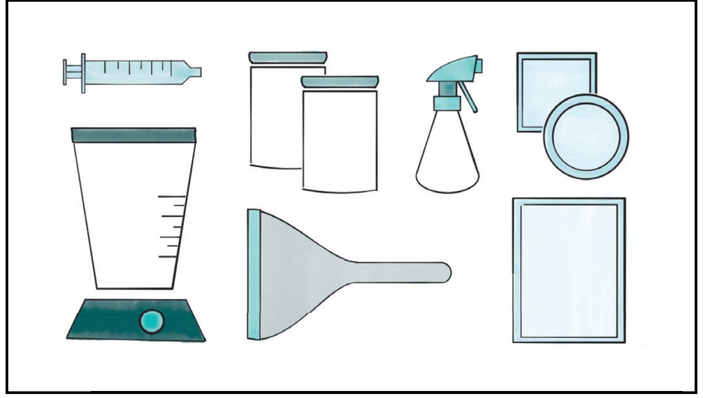
DAY 1
DAY 14
SCOBY
TEA + SUGAR
CELLULOSE
STARTER CULTURE

5.2.2. Algae: alginate bioplastics

Sodium Alginate – NaC6H7O6 – is derived from the extraction of alginic acid, a polysaccharide present in brown algae cells. Once hydrated it forms a viscous gum which is often used as thickener or jelling agent in the food, pharmaceutical and cosmetic industry. The reaction with calcium chloride solution, creates a shrinking in the mixture, and turn it into an hydrophobic and edible material. Such reaction is the same used for spherification in molecular kitchen and food science.



TOOLS



ETHANOL

BLENDER

JARS

SPRAY BOTTLE

MOULDS

SYRINGE

SPATULA

INGREDIENTS

 $(C_6H_8O_6)_n$ ALGINATE

 H_2O WATER

 $C_3H_8O_3$ GLYCERINE

 $CaCl_2$ CALCIUM CHLORIDE

 SUNFLO-WER OIL

PROCESS

- Pour the alginate powder, water, glycerine and any other additive in the blender and mix
- Pour it in a jar and leave it rest overnight to let the air bubbles disappear
- Prepare the calcium chloride solution and put it in the spray bottle

For *thicker bioplastics*:

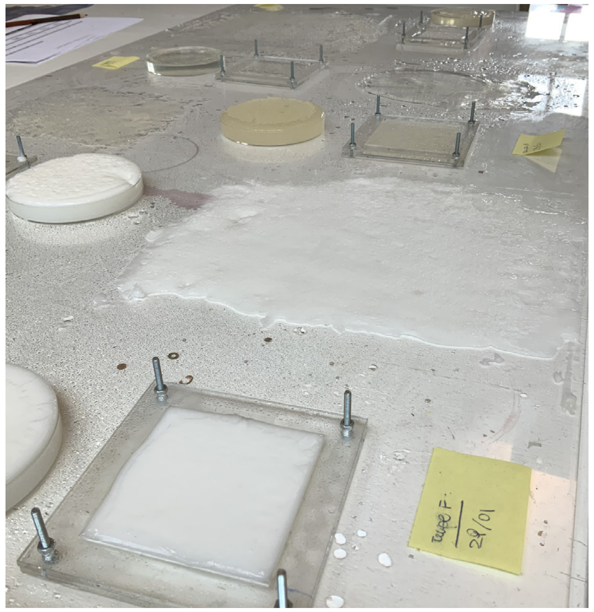
- spray the mould with the calcium chloride solution
- cast the material
- spray it with calcium chloride solution and let it dry

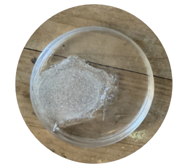
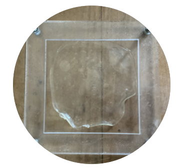
For *thin biofilms*:

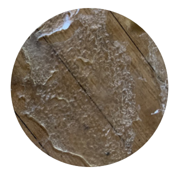
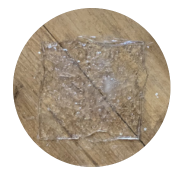
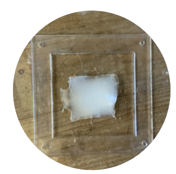
- spray the surface with the calcium chloride solution
- pour the mixture on the surface and smooth with a spatula
- spray it with calcium chloride solution and let it dry

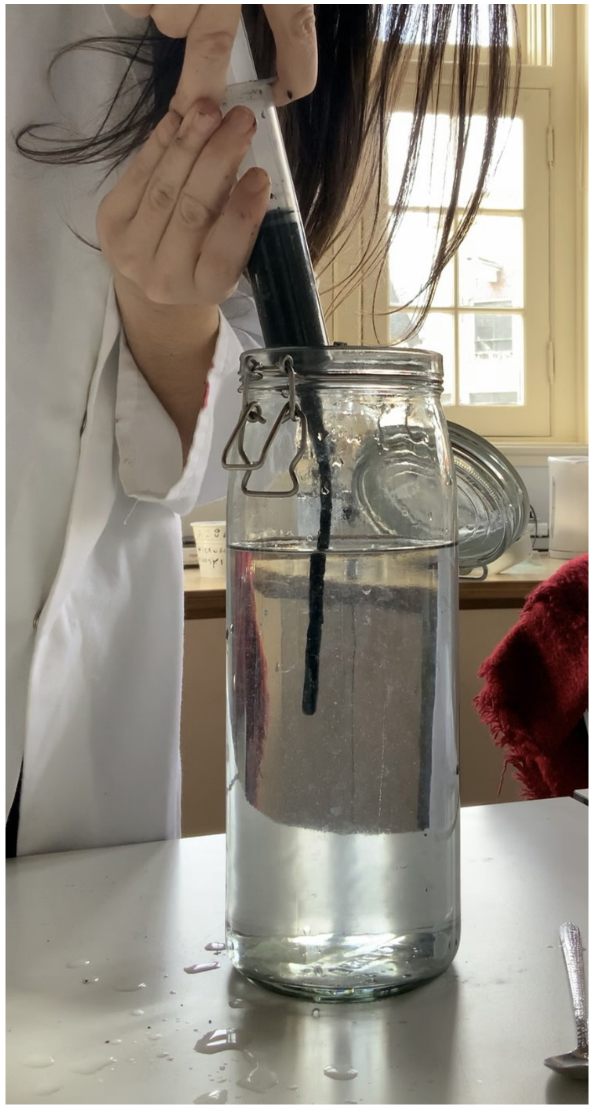
For *strings*:

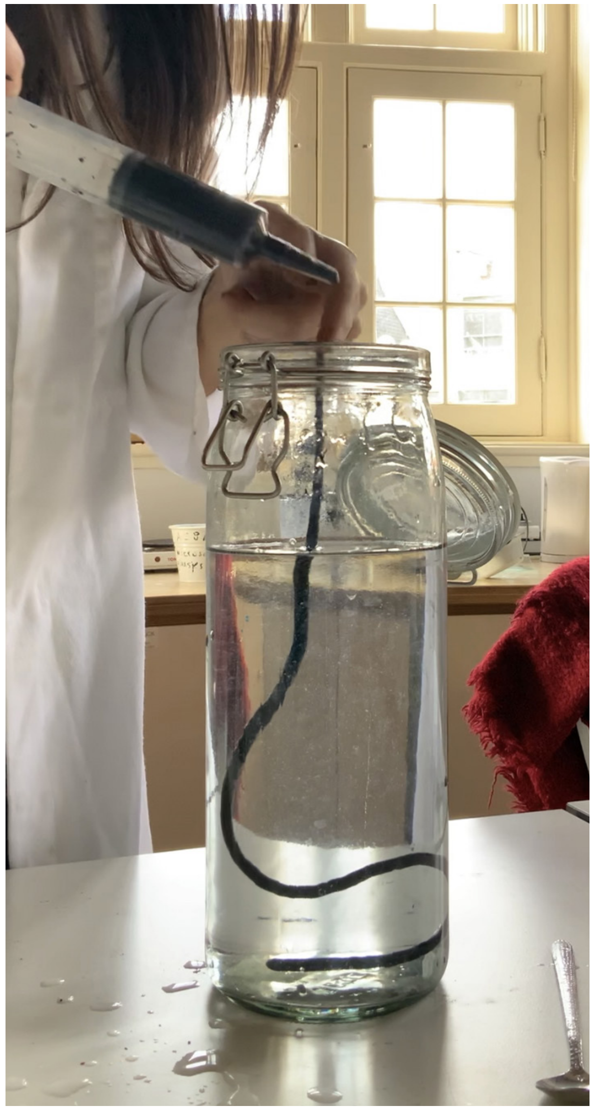
- prepare a vertical jar filled with the calcium chloride solution,
- inject the mixture in the syringe and extrude it in the jar
- collect the strings and let them dry



FILM	MOLD 1 [h 3mm]	MOLD 2 [h 1cm]
RECIPE B [water x1]		
 difficult to spread irregularities and holes thin and fragile	 air bubbles high shrinkage	 little deformation
RECIPE A [water x2]		
 too thin and fragile	 thin almost disappeared with shrinkage	 too thick only the surface shrinks
RECIPE E [water x4]		
 strong right thickness	 little deformation	 too thick too much deformation

RECIPE D [water x1]		
 difficult to spread irregularities and holes	 irregularities and holes	 keeps the shape with little deformation
RECIPE C [water x2]		
 ok but too thin	 high shrinkage (50%) irregular thickness	 too thick too much deformation
RECIPE F [water x4]		
 too thin irregular and fragile	 high shrinkage (50%) irregular thickness	 extreme deformation



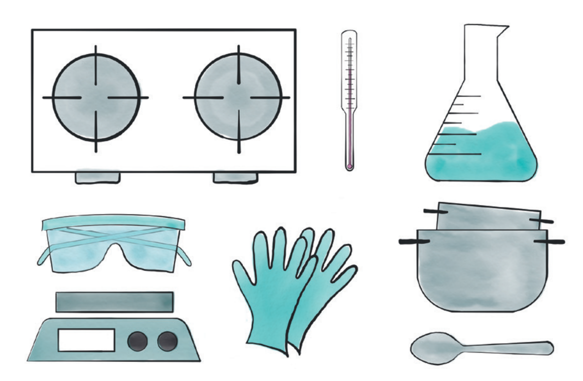


The table in the previous page illustrates the methodology followed for the experiments. The principle followed was to make variations in the recipes proportion and in the moulds used in order to understand the relationship between the recipe and the material morphology.
Starting from two basic recipes (with and without sunflower oil), the amount of water – and therefore the viscosity of the compound – was increased and decreased and each recipe was tested with different thicknesses – from thin film to thicker biopolymer.
This made possible to understand that the more liquid mixtures were suitable to cast thin films, but they appear to be unusable in thicker shapes because of the extreme shrinking and deformation. Thicker shapes can be obtained using the more viscous compounds, but keeping within values below 1cm, otherwise the internal part of the material will remain wet because never in contact with the calcium chloride solution.
The pictures on the left side instead, illustrate the process of making alginate in the form of strings, with the help of a syringe through which extruding the compound directly inside a jar filled with the calcium chloride solution, which will instantly make the viscous mixture solidify. In this case alginate was mixed with charcoal powder to create a composite material. Charcoal confers the final material an higher rigidity as well as a rough texture.

5.2.3. Hair: keratin extraction

Keratin is a sulfur-rich insoluble filamentous protein belonging to the family of the Scleroproteins. It is the main constituent of our nails and hairs, as well as many protective parts of animal bodies such as the outer layer of skin, horns, claws, feathers and scales. It is indeed among the toughest biological materials, able to resist mechanical stress, and therefore used to increase the resistance of the most vulnerable parts of the body. Ketatins can be classified as α-keratin, found in all vertebrates, and β-keratin, found in reptiles and birds. They have a filament-matrix structure and from the mechanical point of view behave as bio-polymers.

TOOLS



STOVE
TERMOMETER
BEAKER
GOGGLES
SCALE
GLOVES
POTS
SPOON

INGREDIENTS

NaOH SODIUM HYDROXIDE

H_2O WATER

HAIR

PROCESS

Liquid Keratin Solution:

- Dissolve sodium hydroxide in cold water
- Prepare a water bath at 50°C
- Add hair
- Stir and keep at constant temperature and agitation for 5h: hair will start breaking until it completely dissolv
- Filter with a strainer

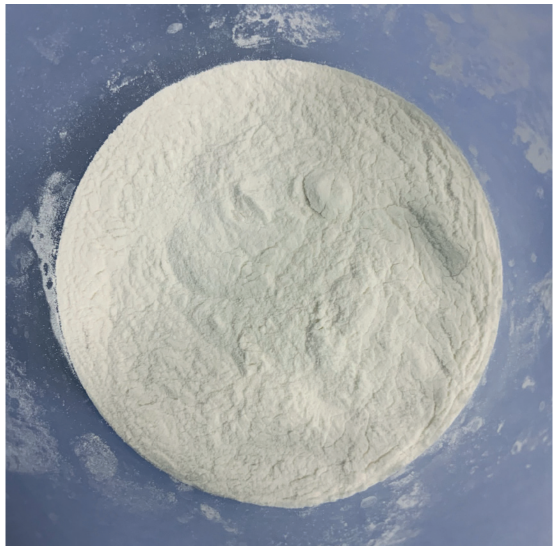
Keratin bio-flm and composites:

- Pour the keratin solution plus additives (glycerol and any other) in the pot and stir for a couple of minutes
- Pour in Petri dishes
- Desiccate in the oven at 60°C until dry

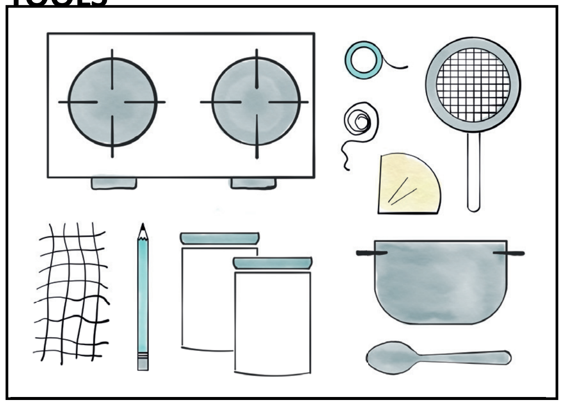
For this experiment hair was collected from hair saloons. After the extraction, keratin was combined with glycerine and seaweed in different grains (from powder to larger pieces), in order to realise materials with variations in thickness, texture and translucency.
The experiment was part of a collaboration with the multi-media artist Bela Rofe for her fabricademy project "Gaia", investigating the interconnection between women and the sea, highlighting the delicate balance among living systems on Earth.

5.2.4. Crystals: alum

Alum, or potassium alum, is a chemical compound made of potassium and aluminium, which crystallises in cubic structure. It has many applications from medicine and cosmetics, to dyeing, flame retardant etc. Crystals formations is obtained through precipitation from a solution: the alum molecules join together forming a crystalline solid. If another material is hanged in the solution the crystals will form around it, and it will act as a scaffold.



TOOLS



STOVE
TAPE
TWINE
COFFEE FILTER
SIEVE
SCAFFOLD MATERIAL
PENCIL
JARS
POT
SPOON

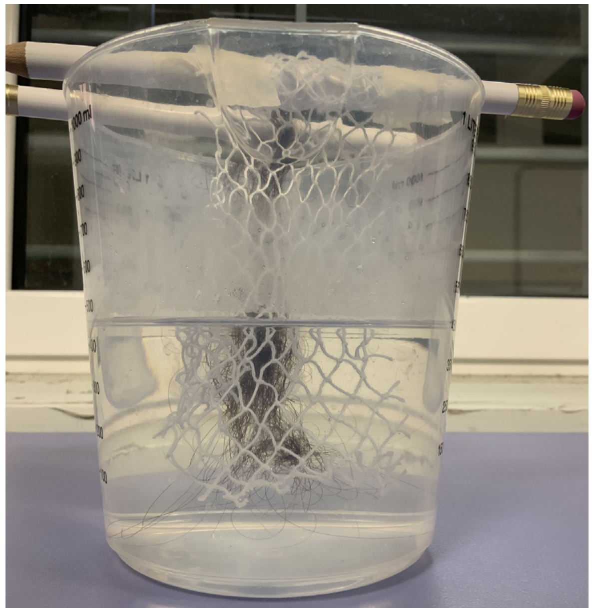
INGREDIENTS

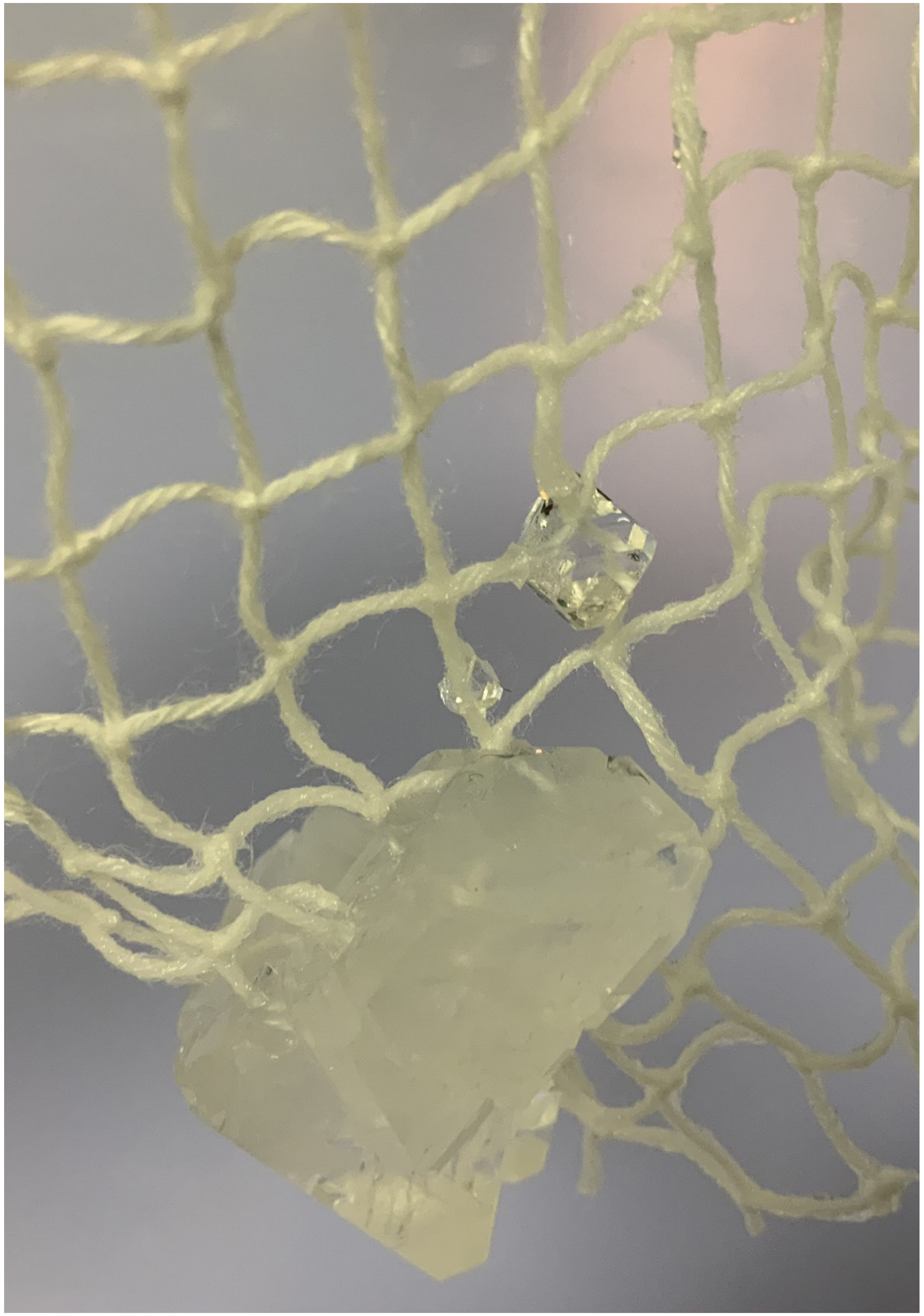
$KAL(SO_4)_2 \cdot 12H_2O$
POTASSIUM ALUM

H_2O
WATER

PROCESS

- Boil the water
- Add the alum and stir until the solution is saturated and it stops dissolving
- Filter the solution to remove any undissolved material
- Place the scaffold material suspended in the jar with the help of pencil, tape and twine
- Pour the solution and wait for crystal formation without moving the jar
- Harvest the crystallised scaffold material and leave it dry

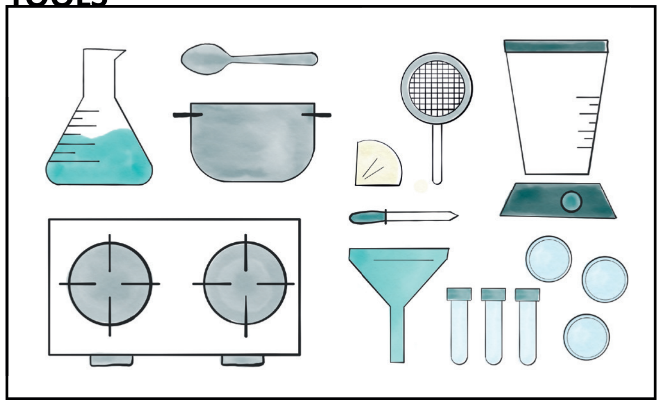


5.2.5. Natural dyes: blueberry

Anthocyanin are water-soluble natural pigments, which can turn in different colours depending on the pH level. Found in many foods (blueberry, raspberry, blackberry, red cabbage, black rice) and more in general in many flowers fruits and plants, resulting in colouration through which attract pollinators or herbivores animals to aid seed spreading. They are responsible also of the red and purple colours of autumn leaves. The anthocyanin can form salts both with acids and bases, and the same anthocyanin can so result in different colours in different plants, according to the acidity of the environment

TOOLS



- BEAKER
- SPOON
- POT
- COFFEE FILTERS
- SIEVE
- BLENDER
- STOVE
- PIPETTES
- FUNNEL
- TEST TUBES
- PETRI DISHES

INGREDIENTS

- BLUEBERRIES
- H_2O WATER
- CH_3COOH VINEGAR
- $NAHCO_3$ VINEGAR

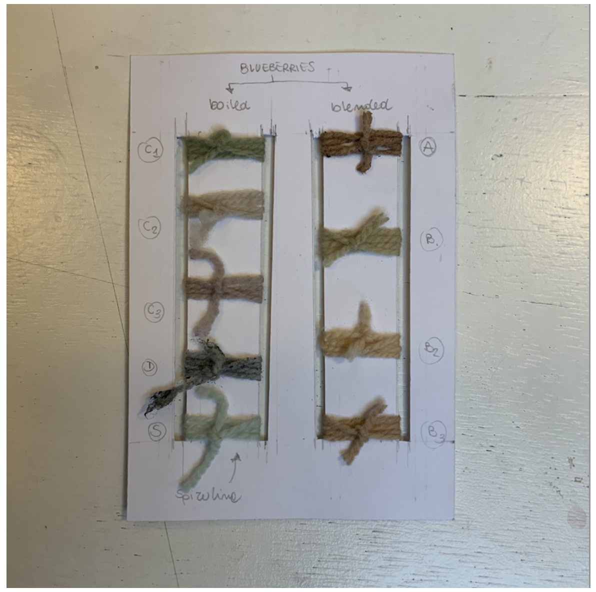
PROCESS

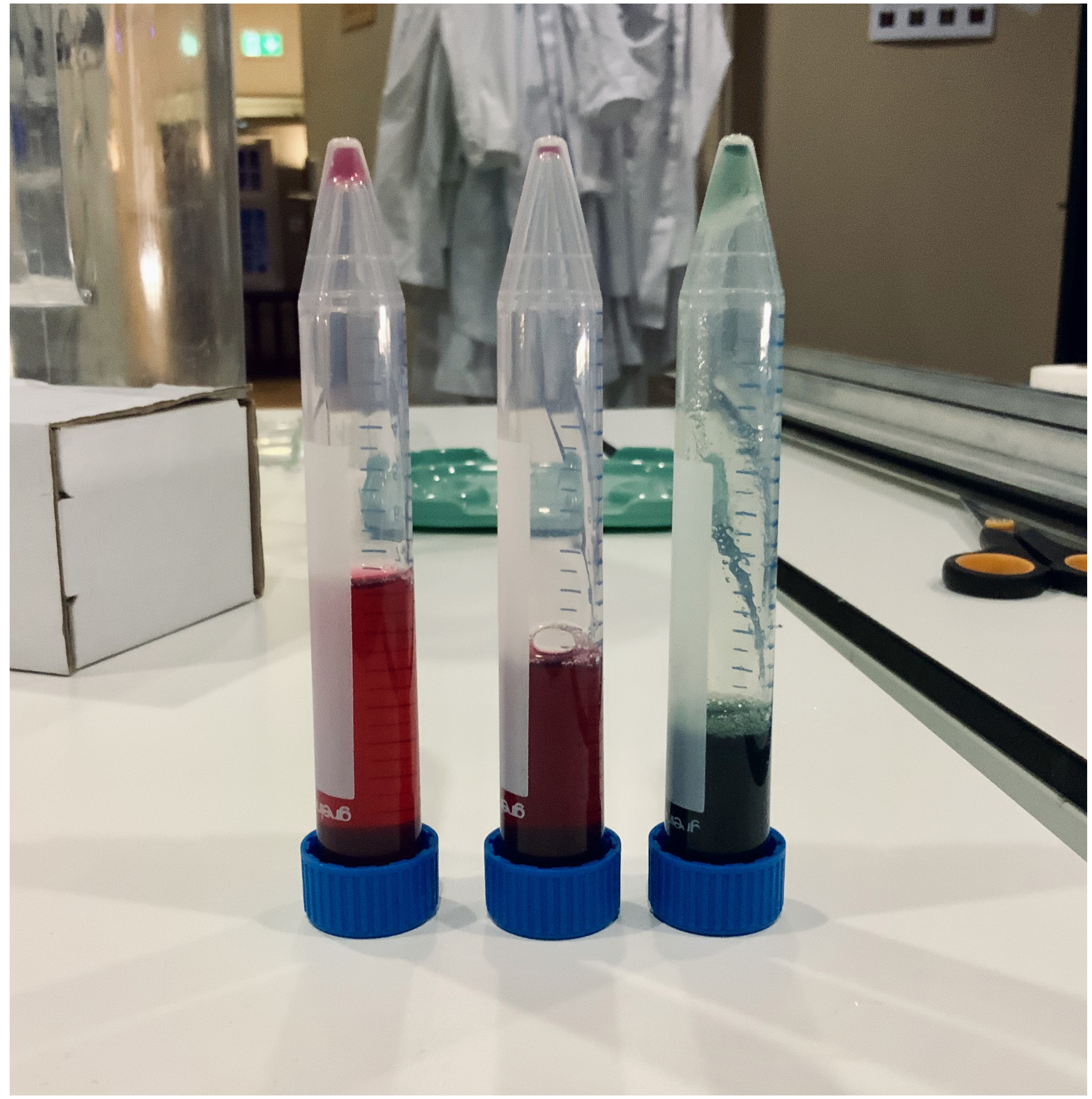
Mechanical separation:

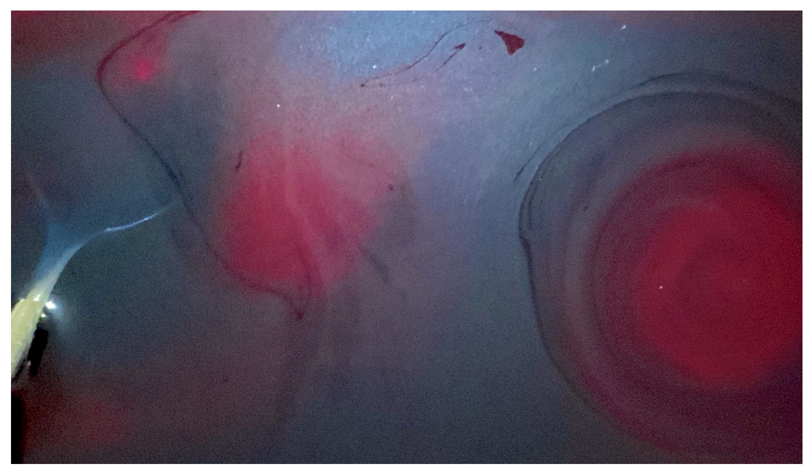
- Blend blueberries
- Filter with a strainer and coffee filters
- Divide the dye in three petri dishes: add baking soda to the first, add vinegar to the second one, and leave the third as it is
- Store in test tubes

Heat separation:

- Boil blueberries for about fifty minutes
- Filter with a strainer and coffee filters separating berries from boiling water
- Divide the dye in three petri dishes: add baking soda to the first, add vinegar to the second one, and leave the third as it is
- Store in test tubes



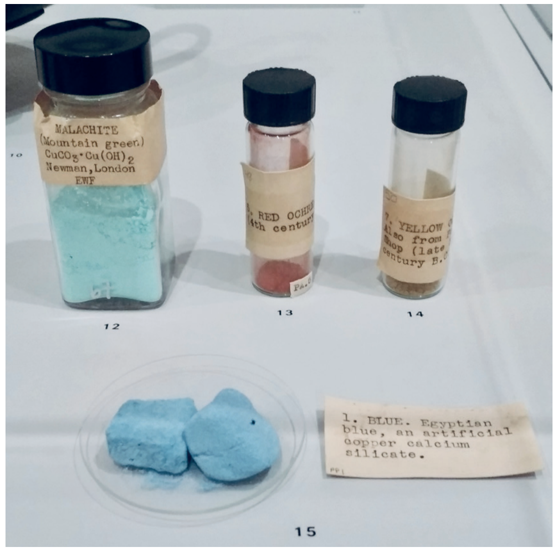




The dye was extracted from blueberries through heath and mechanical separation. The dyes obtained were then reacted with acids and bases through which changing the pH and consequently the colour.
Fabric threads were then dipped into the dyes to get a colour palette, however the threads weren't treated with the mordants required to retain the colour on the fabric, and therefore the threads' colours appear much lighter and mild then the actual dye.

5.2.6. Inks: charcoal

The first form of ink was realised grinding iron-rich rocks into pigment 40,000 years ago. Early humans indeed, used earth pigments such as ochre and chalk, or carbon black obtained from the burning of animal fats to paint on cave walls. Later, in 2500 B.C. ink was independently invented in China and Egypt and pigments started to be produced in large scale, new pigments were obtained from minerals and vegetable dyes vere discovered in Egypt.
With the Reinassance and the spread of interest in art, a huge number of new pigments were created from natural sources until, in 1704, the German colour maker Johann Jacob Diesbach created the Prussian blue by accident in his laboratory, marking the birth of synthetic colours.
With the growing awareness on the ecological damages caused by synthetic dyes and pigments, today we are refocusing our attention to nature as a source for colours, which can provide us with both natural and biofabricated pigments.



TOOLS

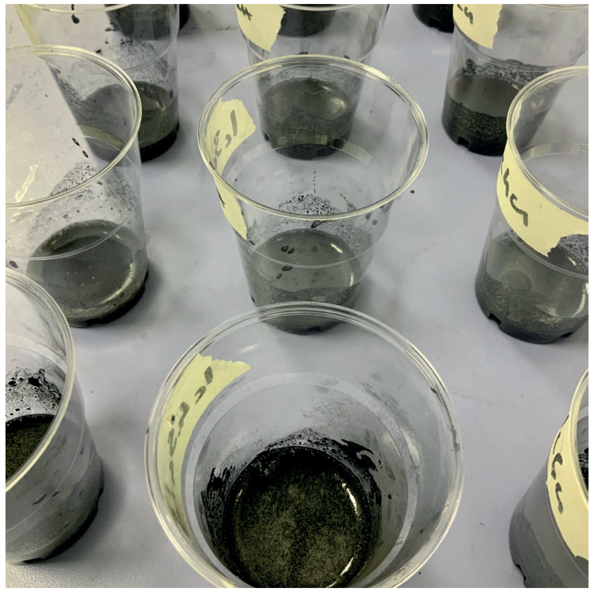
MORTAR & PESTLE
FILTER
STRAIN
GLASS CONTAINERS
MEASURING CUPS
SPOON
BOWLS

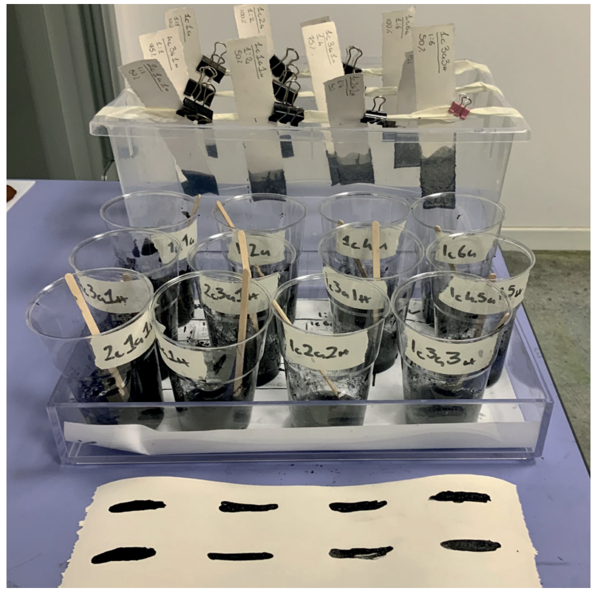
INGREDIENTS

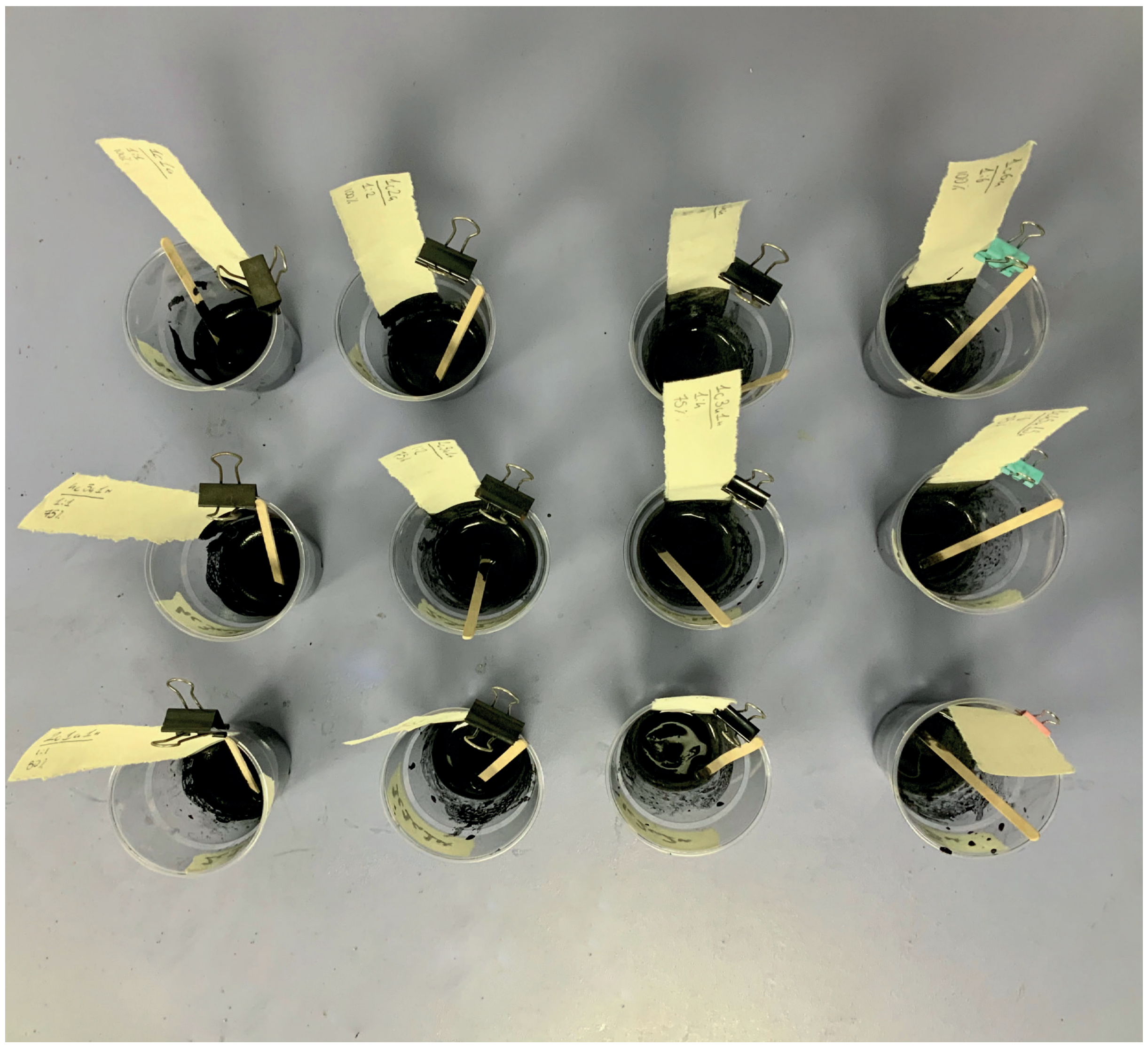
C	H_2O	$C_{15}H_{20}NNA_{O4}$
CHARCOAL	WATER	GUM ARABIC

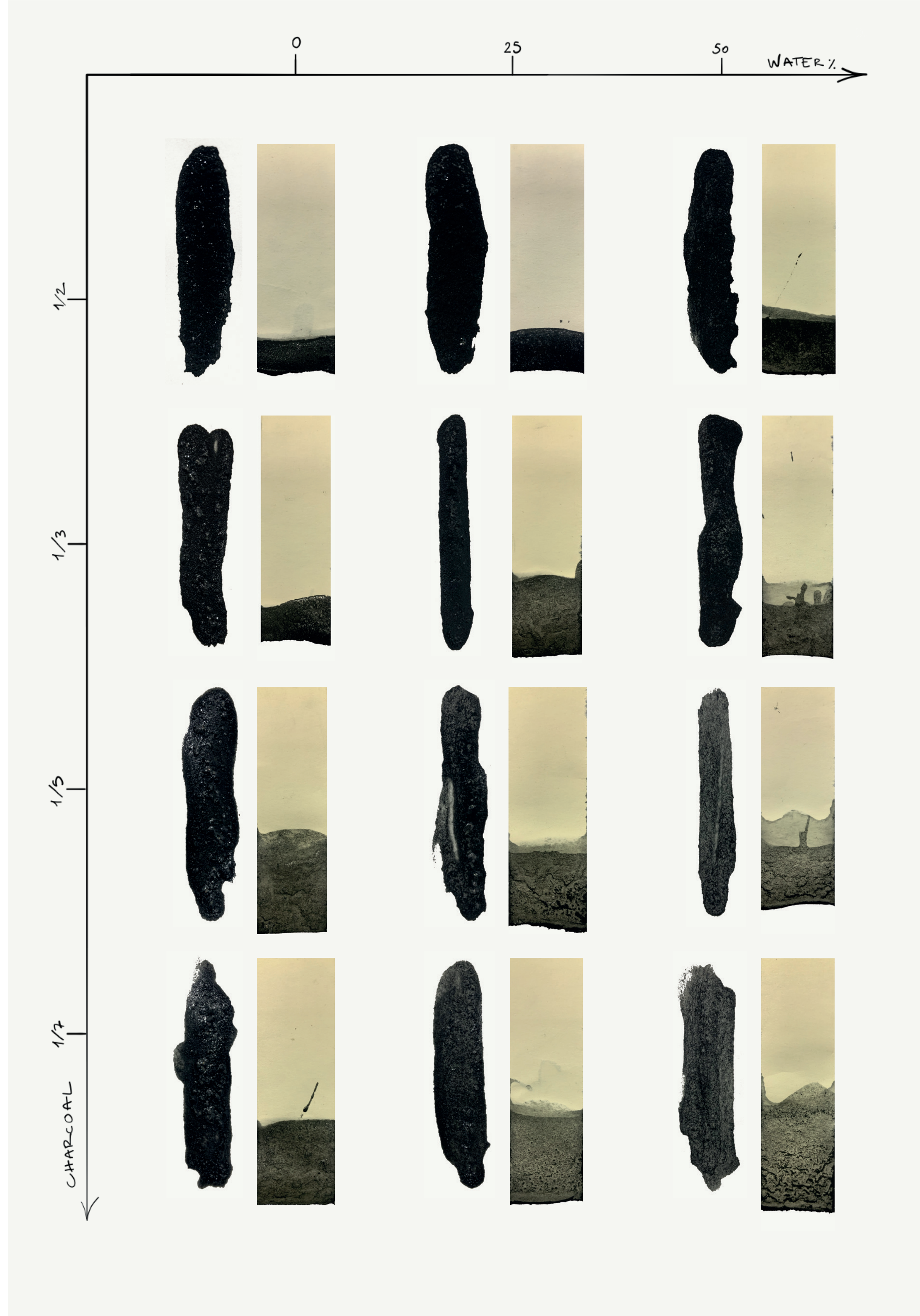
PROCESS

- Turn the charcoal into powder with mortar and pestle;
- Put the powder in a bowl, gradually add water and gum arabic alternating;
- Stir;
- Filter with coffee filters to remove solid parts;
- Pour in a glass container and shake.








0
25
50
WATER %
1/2
1/3
1/5
1/7
CHARCOAL

Cross-contamination and interdisciplinarity

Waag Society: TextileLab & OpenWetLab

The basic experiments here collected have been carried out within the field research conducted at Waag Society. This allowed the author to experience the fact of working in a multi and trans disciplinary environment where people with different backgrounds – science, art, design, education – and from different parts of the world is gathered, resulting in a disciplinary and also cultural contamination.

The activities carried out in Waag's laboratories – TextileLab, OpenWetLab, FabLab – involved many different projects, some of them design-oriented, others science-oriented, some structured to address specific issues or topics while others more grounded on experimental research. Despite the diversity characterising the many ongoing research projects, the physical environment of the laboratories fostered a continuous process of contamination and blending of skills, ideas and perspectives. Using open co-working spaces as well as sharing the lab spaces, put together all the different professionals, students and interns working there, hence also a small chat during a coffee break could turn into the sharing of observations, opinions, concepts etc. This triggered a process of knowledge exchange, as for instance hearing the opinion of a microbiologist on your design project or vice-versa, and often resulted in collaborations for the experimentations, with a blend in the different approaches: designers conducting experiments following scientific protocols while guided by biologists; material designers supporting artist in the biomaterial production; methodology confrontation and development on common topics between educators, scientists and designers, and so on.

Everyone made available her/his skills to others, and shared her/his experience on different topics. This means a growth for all, and feeding a continuous process of learning and reframing your individual perspective adding every time a different piece able to enrich it.
The Hands-on approach adopted within the experimentations makes the implicit process explicit, thereby allowing each one to "learn consciously from each project and thus become empowered through the process" (Swann, 2002). Working in shared spaces and collaborative environments rather than in isolation, means to vicariously learn also from what the others do, find common interest and topics of investigation, or discover something completely new from someone else's project that can be precious for your research.

Waag's core values are openness, fairness and inclusivity. Open and shared knowledge is essential for the advancement of scientific research, and more generally of society, opposed to competitiveness and individualism that often characterise the academic research field. In this context indeed, collective advances are often subordinated to the pursue for individual growth, in contrast with the core principle of research, that should be always aimed at the joint growth of science and humankind.

I. OpenWetLab, Waag Society
II. TextileLab Amsterdam, Waag Society

III.


IV.

III-IV. TextileLab Amsterdam, Waag Society

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CHAPTER 6

FERMENTATION
DESIGN WITH LIVING SYSTEMS

ABSTRACT
The second stage of the experimentation was focused on microbial nanocellulose fabrication. The material is the byproduct of the fermentation process of a Symbiotic Culture Of Bacteria and Yeasts or SCOBY, traditionally used for kombucha production. The experimentation started from the process as way to interact with the living system and understand how to affect the material sensory properties intervening on the growth conditions. Following the standard kombucha brewing process indeed, besides the advantages in terms of technical-performative features, the final material, with his brownish colour and acidic smell, does not result very appealing from the aesthetic-perceptual point of view. Acting on the growth process through changing the kind of nutrients used, a material palette was realised, made of samples equipped with different sensory properties – colours, textures, smells, etc.
As following step, starting from the exploration and understanding of material properties and peculiarities, three macro application scenario have been developed: sensory packaging, augmented paper, skincare. In any of them features such absorbency, hydrophilicity, short lifespan, adhesiveness or multisensoriality, doesn't represent a weakness but rather the product added value.
After investigating microbial cellulose to the micro-scale of processes and materials, as well as to the meso-scale of products, the final step moved the investigation to the macro-scale of production systems, envisioning future prospects for development and implementation of alternative production-distribution-consumption systems grounded on circularity and collaboration. The goal is to make biofabricated materials available through everyday products, providing an easily and rapidly accessible alternative to synthetic materials, favouring at the same time a familiarisation and demystification process towards biofabrication.

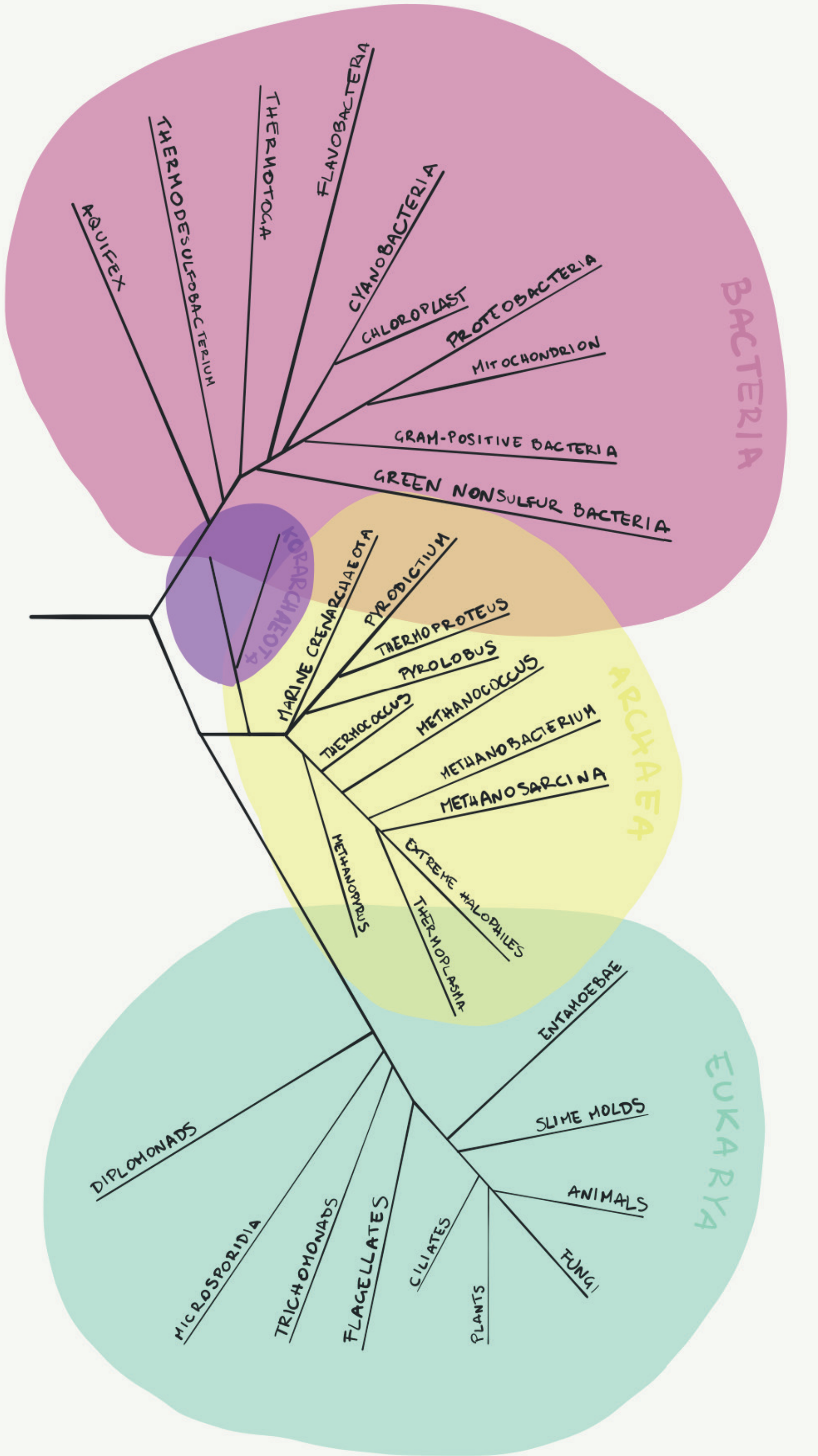
6.1. Fermentation

The majority of terrestrial living organisms are invisible to naked eye. Microbes indeed have inhabited Earth for 3.5 billion years, evolving and adapting to nearly every type of environment. They constitute the two thirds of life on Earth, which is classified into three domains: Bacteria, Archaea and Eukaria. The first two domains consist of prokaryotes, single-celled organisms with no nucleus. The main difference between them is that Archaea includes microorganisms which often live in extreme environments such as deep sea or volcanoes. Eukaria instead includes eukaryotes – organisms whose cells have a nucleus – and is the only domain which contains multicellular and visible organisms.
Microorganisms are essential for life, without them and the symbiosis with plants and animals life on earth wouldn't be possible. They are at the beginning and at the end of food chains on the planet, making possible the cyclical transformation of matter and energy. In the oceans microalgae are responsible for the production of half of all the oxygen in the atmosphere; in the soil fungi and bacteria convert the organic matter from dead animals into new raw materials which can feed plants, and within our body intestinal bacteria help us digest food.
Microbes are therefore biological catalysts involved in many essential processes as decomposition, nutrient production and energy flow, production of foods, drugs and vaccines, bioremediation and also infectious diseased. Microbial growth is influenced by several factors: incubation temperature; pH, according to wether the microorganisms are acidophiles, neutrophiles or alkalophiles and therefore can grow in acidic, neutral or alkaline environments; carbon source, distinguishing between autotroph organisms which can produce their own food by reducing carbon dioxide, and heterotroph organisms which use organic molecules for food production; and finally oxygen availability, which will determine the possibility to implement aerobic or anaerobic growth processes.
One of the most known and used microbiological processes is Fermentation, a technology through which growing cells in a large sca-

le with high efficiency. Fermentation is a metabolic redox process which produces chemical transformations in organic substrates. Humans have used fermentation to produce food and other useful substances from ancient times. It is widely used for food preservation, as well as for the production of alcoholic beverages such as bourbon whiskey, mezcal, sake or vodka. Many of the most common foods and beverages such as cheese, bread, wine and beer are produced through fermentation processes. In Asia lactic bacteria fermentation is a widely used technique for the preparation of vegetable products typical of the diverse regions of the continent; many of them aren't diffused worldwide, but others such as Korean Kimchi made from Chinese cabbage or Japanese Miso, are also known in the Western countries. Other fermented foods are pickles, sauerkrauts, table olives and even coffee, whose production process includes a fermentation stage for the elimination of the shell that envelopes the grains. Another example drawn from eastern culture and currently diffused worldwide is Tempeh, traditional Indonesian food made with soy beans inoculated with a type of mould which creates a dense mycelium which wraps the beans into a compact compound. Besides food, fermentation technology is widely used also for bioethanol production, as well as in the medical field for the production of antibiotics and drugs in general.

6.1.1. Kombucha and Microbial Cellulose

An ancient fermented product which has been rediscovered in recent years is Kombucha. Also known as "tea fungus", Kombucha is a fermented tea originated in Manchuria, northeast China, around 220 B.C., appreciated for its detoxifying and energising properties. Later, in 414 AD, a Korean doctor named Kombu used it to cure the digestive troubles of the Japanese king, making it popular in Japan as Kombucha (Dutta & Paul, 2019). Fermented tea consumption was a common practice also in Russia, especially in the Kargasok region where people used to have an healthy lifestyle and showed retarded ageing with an average lifespan exceeding hundred years (Williams, 2001). The high probiotic content of the drink makes it highly beneficial for human health. Many recent studies highlighted the numerous beneficial properties of Kombucha which acts as detoxifying agent, immune system fortifier, antimicrobial, antioxidant, and even anti-carcinogenic (Dutta & Paul, 2019).
Kombucha is obtained through the microbial fermentation of black or green sweetened tea by a symbiotic culture of bacteria and yeasts



1.

1. Domains of Life, biological taxonomy

or SCOBY. The process consist in two steps: first the yeasts transform sugars into ethanol, then bacteria turn ethanol into acetic acid, releasing as byproduct nanocellulose fibrils. Such nanofibrils float in the culture medium layering on its surface and bind together giving rise to a strong tridimensional cellulose biofilm. The nanocellulose layer presents an entangled three-dimensional structure with a unique porous matrix, good mechanical properties, and high water absorption, surface area and crystallinity.
Cellulose is the most common polymer available in nature. It is the main component of vegetal biomass and can be synthesised also by Gluconacetobacter bacteria strains as xylinus, which can be found within the fermentation of sugars and plant carbohydrates, as on damaged fruits and flowers or unpasteurised juice, beer, and wine (Gatenholm & Klemm, 2010).
Cellulose obtained from vegetable sources requires chemical treatments and the employ of highly polluting chemical products such as chlorine gas, caustic soda, carbon monoxide, carbon dioxide etc., because of the presence of other components as lignin, hemicellulose or pectin.
Cellulose from bacterial sources instead is produced in its pure form, which provides higher flexibility, higher hydrophilicity, and drug load-release properties (Dima et al., 2017). Moreover, its crystalline morphology and its structure consisting of a nanoscale fibre network architecture, determine remarkable mechanical properties despite containing up to 99% of water while in the culture media (Gatenholm & Klemm, 2010). As emerging biofabricated material it finds application in the biomedical field as biological implant, wound and burn dressing material, and scaffold for tissue regeneration, as well as in the cosmetic, paper and food industry.

6.2. Sensory Exploration

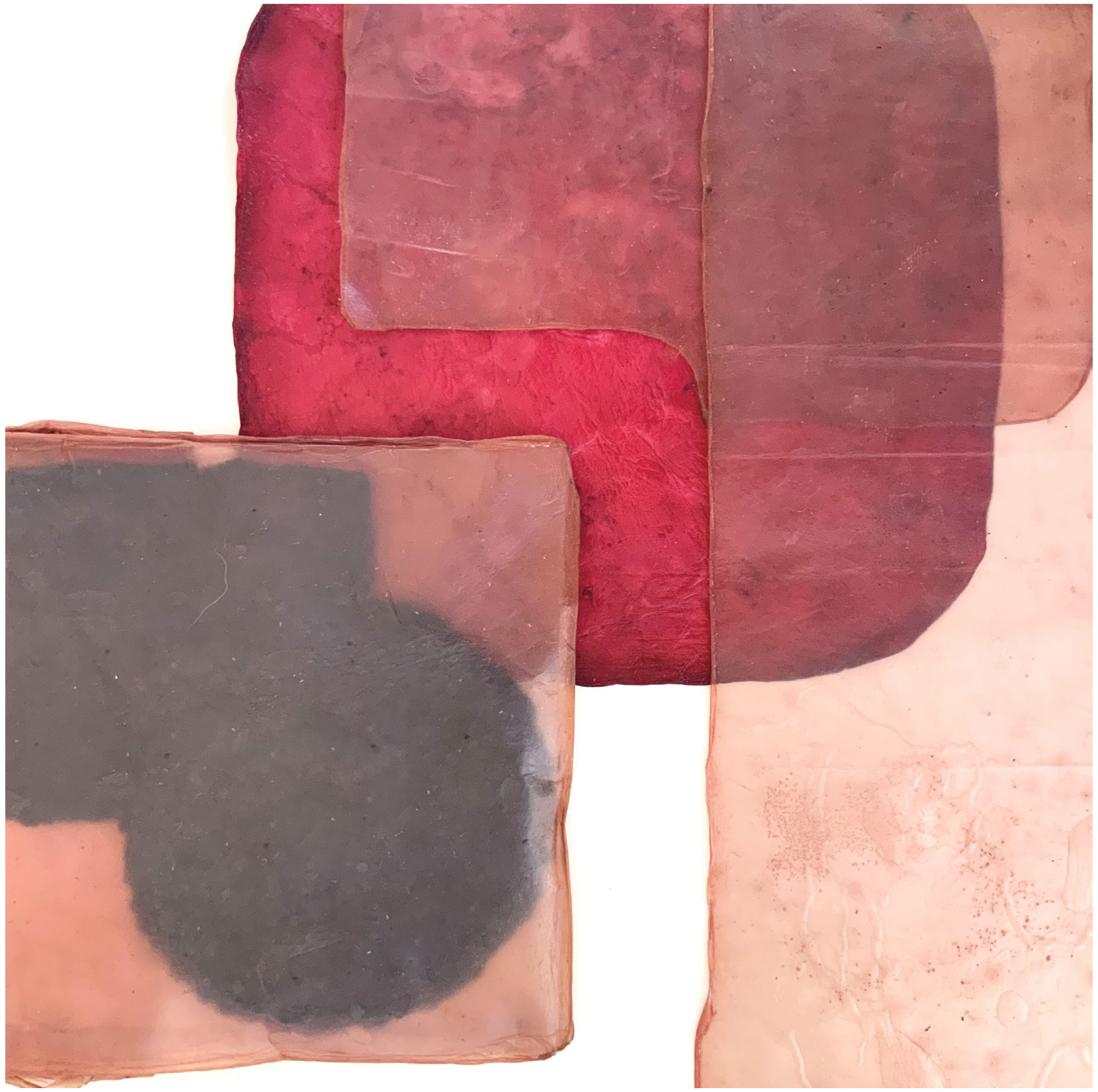
The standard Kombucha brewing process produces microbial cellulose of a brownish colour which can vary from light to dark according to the colour of the tea used. Moreover it keeps the strong vinegar smell typical of the fermentation process also once dried and therefore, despite the many advantages in terms of technical, performative and productive features, from the aesthetic and perceptual point of view the final material doesn't seem to be very appealing and sometimes even unpleasant. For this reason the experimentation on microbial cellulose was focused on the exploration of the sensory and perceptual potential of the material.
The starting point was to understand and therefore interact with the production process, in order to be able to experiment with perceptual features, suggest new rules and imagine new applications.
The aesthetic-perceptual aspect, twist of material and immaterial features, involves the user on the emotional level establishing an emotional interaction which can condition – positively or negatively – the way materials and products are perceived (Zafarmand, Sugiyama, & Watanabe 2003; Faucheu et al., 2015). It this therefore an essential element responsible for the diffusion of new biofabricated materials, since it can decisively determine their appreciation and consequent use.
Users' perception of the products they see or use is influenced by a set of physiological, psychological and cultural factors (Zuo, Hope, Castle & Jones, 2001). These factors are determined by sensory properties result of materials' physical variables, user's psychological perceptions triggered by sensations, and any intangible aspect related to materials' "hidden character" (Asbhy, 2014) as a metaphor for meanings, which acquire cultural connotation during the interaction with the user.
Sensations are chemical stimuli, resulting from the contact between users and their environment (product, material etc.). They refer to immediate, certain and direct experiences which lead to the conscious awareness of qualities or attributes of the physical environment (Zuo, 2010). Perception on the other hand, is the result

1. The use of colours in design products follows specific meanings: black was commonly used for technological products intended for professionals; the combination of black and red was used to express strength and power recalling the colours used for Walter PPK gun, which had a red dot on its black body to gave the gun safety an high visibility; in the packaging field blue and green evoke images of genuineness and naturalness and are often used for food products. Colours however acquire completely different meanings according to different cultures and traditions, and the most representative example is the different perception of black and withe colours in the western and eastern cultures: in China white is the colour for mourning, it is associated with death, while in the West is the colour for purity, holiness and peace, used for weddings instead of funerals – typically symbolised by black colour

of cognitive processes that originate from sensations. Sensation and perception can't be split, they are part of a unified subjective-objective interaction process. The objective side is related to sensory properties which exist physically outside of us, while the subjective one is related to the interpretation of such properties carried out within our brain (Zuo, 2010).
Besides objective sensory properties, perception is then influenced also by the cultural framework and can vary over time, geographical context and from person to person. Products and materials are indeed vehicle of symbolic meanings and cultural values. The designer act as a communicator and the message is conveyed through the product's semantics, according to the socio-cultural meaning[1] with which any colour, form or texture is equipped (Krippendorf & Butter, 1984).
This means that aesthetic-perceptual aspects of materials and products can reflect the values and cultural dimension emanating from the socio-economic system, but, on the other hand, can in their turn embody and communicate new values, gradually pushing the user towards new ways of behaving and thinking. In the case of biofabricated materials, instead of trying unsuccessfully to imitate the aesthetic perfection and finitude representative of the cultural framework of industrial revolution, synthetic materials, dominion of man over nature, progress and exponential growth, designers should embrace new aesthetic values and languages which could reflect the will for a new mutualistic relationship with nature opposed to the parasitic model of the current industrial system. The irregularity, roughness or imperfection of biofabricated materials expresses their process of growth, the life behind it and even death, and therefore the cyclical and transitory nature of all the matter on Earth.
Within the perceptual investigation on microbial cellulose, is fundamental to remember that perception is a cross-sensory process. The reality we experience is synesthetic, whether we are conscious about it or not. Sensory events can't be experienced in isolation since during any sensory experience senses work simultaneously acting intermodal correspondences and cross-talks within the brain, which result in multiple inputs from different senses related to the same experience (Cytowick, 2018; Schifferstein & Wastiels, 2014; Dal Palù & Lerma, 2015; Schacher & Adolphe, 2011). Therefore senses cannot be isolated and separately investigated if the object of the investigation is the real human behaviour (Faucheu et al., 2015). Despite this however, in the design process often priority is given to the visual aspects – first form of interaction with the user –, underestimating how other perceptual modalities acquire increasing importance during the use, often overtaking the role of vision. Tactility for instance guarantees emotional involvement, is through touch that we "access the world and ourselves" since birth (Fiorani, 2020). Working with sensoriality and perception as designers, we need to be aware that materials speak to all senses providing a synesthetic knowledge of the world (Fiorani, 200), and therefore we have to "enlarge the horizon to expand consciousness with respect to the cross-sensory interplay of everyday life" (Haverkamp, 2012).
The brain is not a "passive antenna" (Cytowick, 2018), it constructs its reality elaborating, merging and interpreting the sensory stimuli it receives. Perception is not the mere sum of isolated sensory stimulations, and we can't interact with the material's sensory features as separate independent channels. We need to design the overall material experience, looking at semantics and sensoriality as tools of designers, not simplistically as well distinguished puzzle pieces on which intervening separately, but as a complex entanglement where acting on one of its parts means to modify it as a whole.

6.2.1. Growing Experiments

The main thing highlighted by designing with living systems is the loss of the full control of designer over the material. This however doesn't mean that we are at the mercy of the microorganisms which take control of processes and results, but that we have to find the way to interact and collaborate with them.
We are interacting with complex systems, which means that systemic properties emerge from the interaction among its elements. We have then the possibility to design boundary conditions that will affect the system's behaviour, implementing in this way processes that can be actually controlled and reproduced.
Any living system is an open system, so by definition "context-sensitive" (Minati, 2004). This means that when working in a controlled environment as a microbiology lab, we can set the environmental conditions acquiring higher control on the process and therefore on the final result. On the contrary, when working in non sterile conditions the living system will be affected by the environment, characterised by specific conditions changing from time to time and from place to place. It is therefore impossible to replicate processes in a standardized way, but is possible to understand which factors affect given features, and act consequently to manage the emergent properties of the material.
When working with microbial cellulose, sensory properties aren't something that can be modified singularly as happens for instance with do-it-yourself bioplastics, where is possible to change the sample's colour just adding an ingredient to the recipe. In this case they are a result of the overall process, reflecting quite clearly the multi-sensoriality of perception and the interconnection of senses.
The growth environment consists of three main parts: the biological environment which is the pure culture and therefore the SCOBY; the chemical environment which is determined by the components of the culture medium; and the physical environment, influenced by temperature, pH, humidity, presence of other microorganisms and so on.
The culture medium, and therefore the food used to feed the microbial metabolism, is what determines at the same time the colour, the

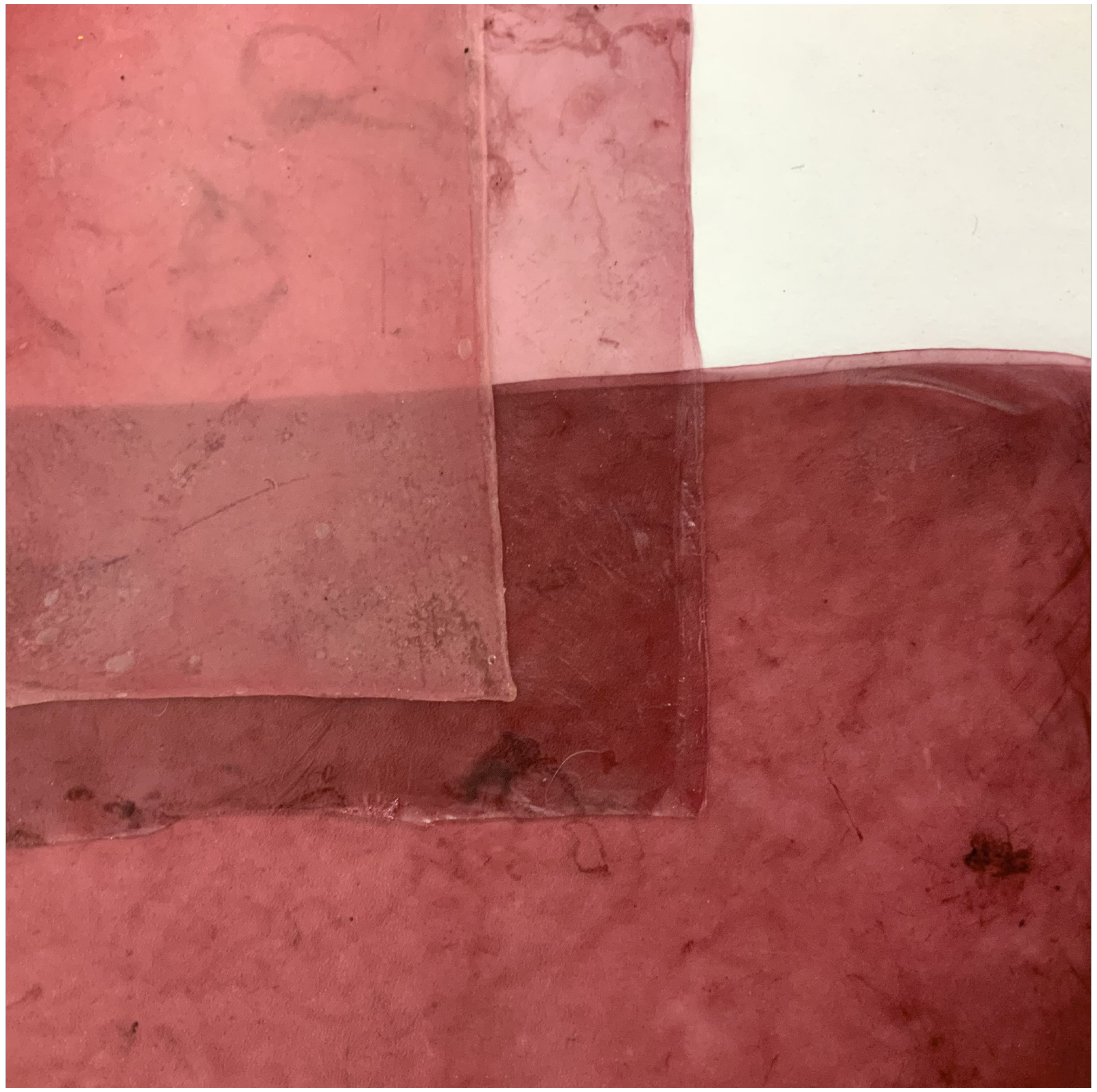
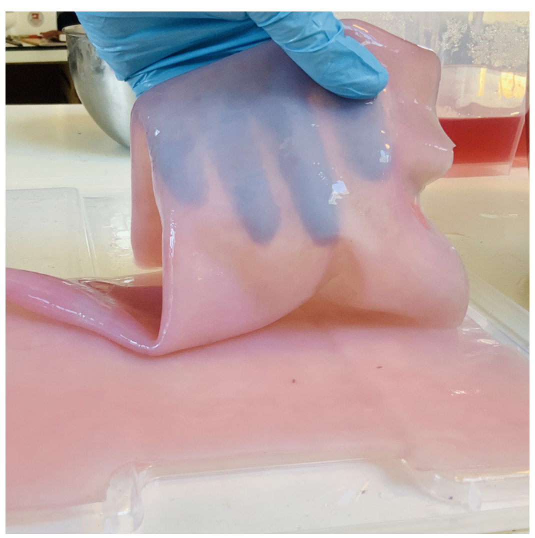


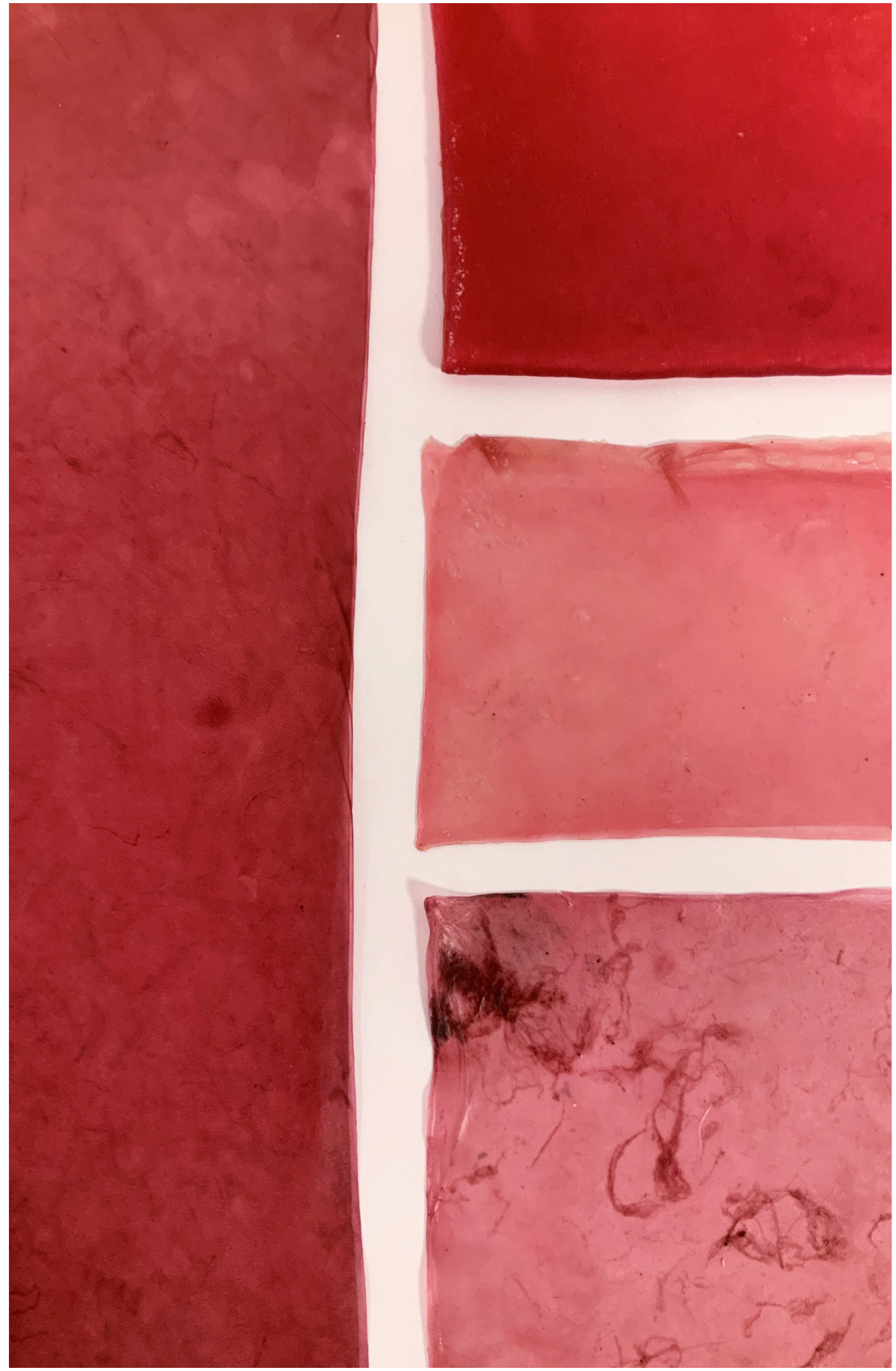
Blueberries

Samples fabricated through blueberry dye fermentation.

Blueberries naturally contain sugars, here used as food source for the scoby. The dye was obtained through heat separation (as described within the basic experiments) and used as culture medium.

Different concentrations can be obtained diluting the dye with water in order to get different shades ranging from pale pink to dark purple colour, and varying the thickness of the material is possible to increase or decrease its transparency.



smell and the texture of the material, involving all sensory channels. The final colour of the material is a direct consequence of the colour of the sugars used: eating coloured sugars microbes will produce nanocellulose filaments of the same colour. This means that using a dyed culture medium where the colour is not determined by sugars or other food sources will not result in a coloured material.

The experiments acted on the chemical environment of the culture, and therefore on the food given to microorganisms in terms of quality and quantity of sugars and ethanol available.
Fruit and vegetables as for instance blueberries, red cabbage or citruses, represent a good sugar source and can be exploited also as food industry production waste (in the form of peels and other byproducts). The sugars already contained in many fruits and vegetables represent an extra food supply which enables us to decrease the amount of sugar added to the culture medium, or otherwise increase the growth rate.
For the same principle alcoholic beverages as wine or beer act as extra food supply too, providing an additional amount of ethanol to be digested by bacteria. This is responsible for a quicker growth, and the possibility to fabricate thicker materials. Besides sugar and ethanol also tannins are elements whose presence facilitates microbial growth, and therefore beverages that contain them as tea, coffee and wine represent a valuable food source for cellulose production.

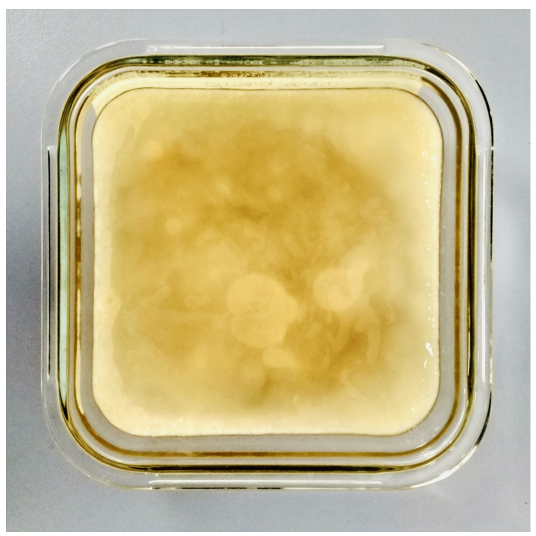
Alcohol: beer, wine

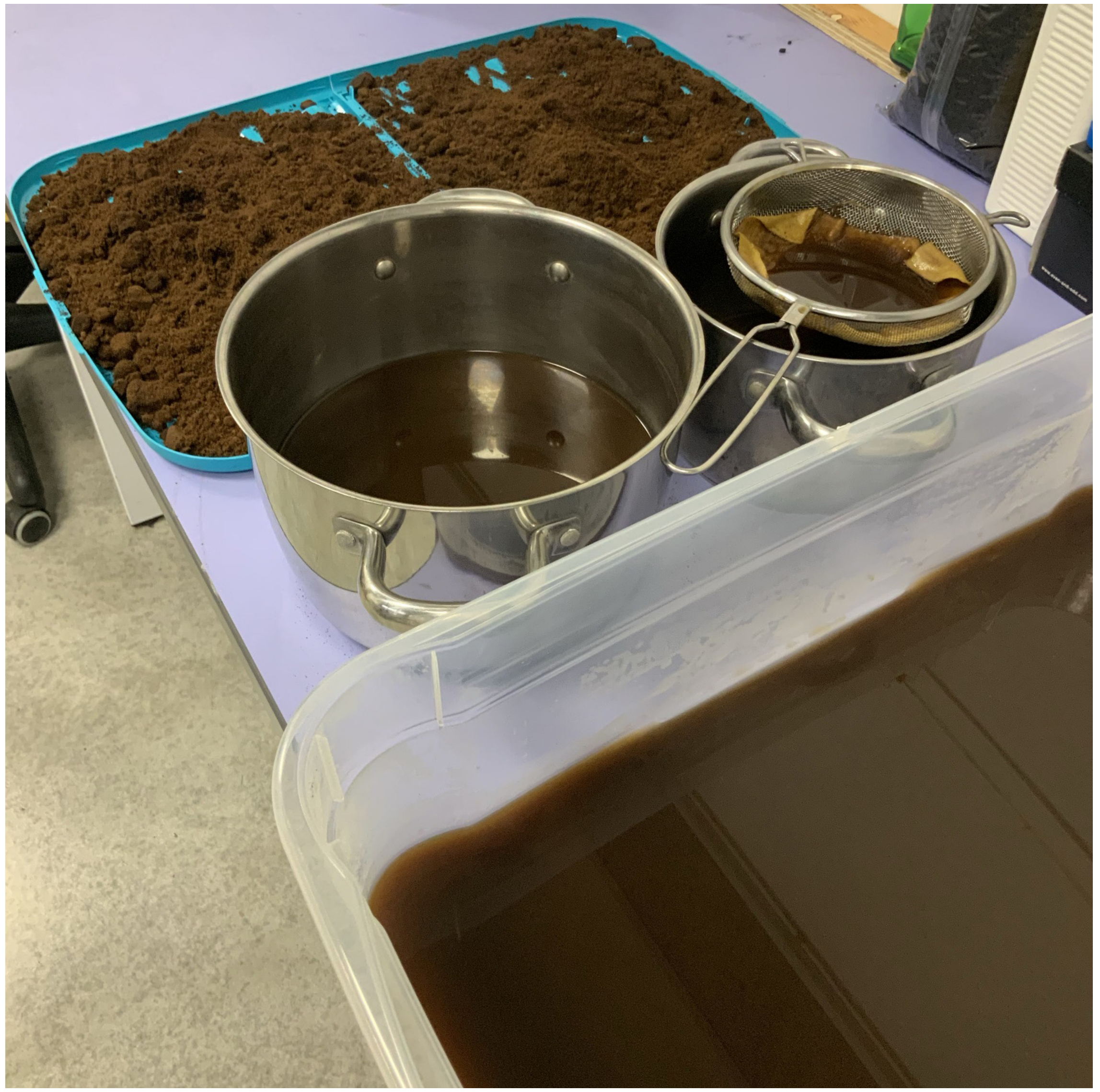
Using alcoholic beverages as culture medium will provide a quicker growth and therefore the possibility to harvest thicker materials.

Beer will produce cellulose in shades of beige and brown. As in the case of tea different kinds of beer — lager, dark, red, etc — will result in different colours.

White Wine will result in a pale natural colour, while Red Wine will result in a dark purple-red colour. Even in this case, through changing the concentration of wine is possible to obtain different shades from dark to light.



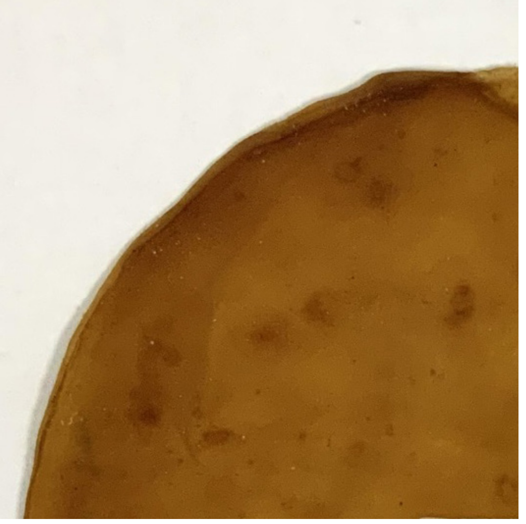



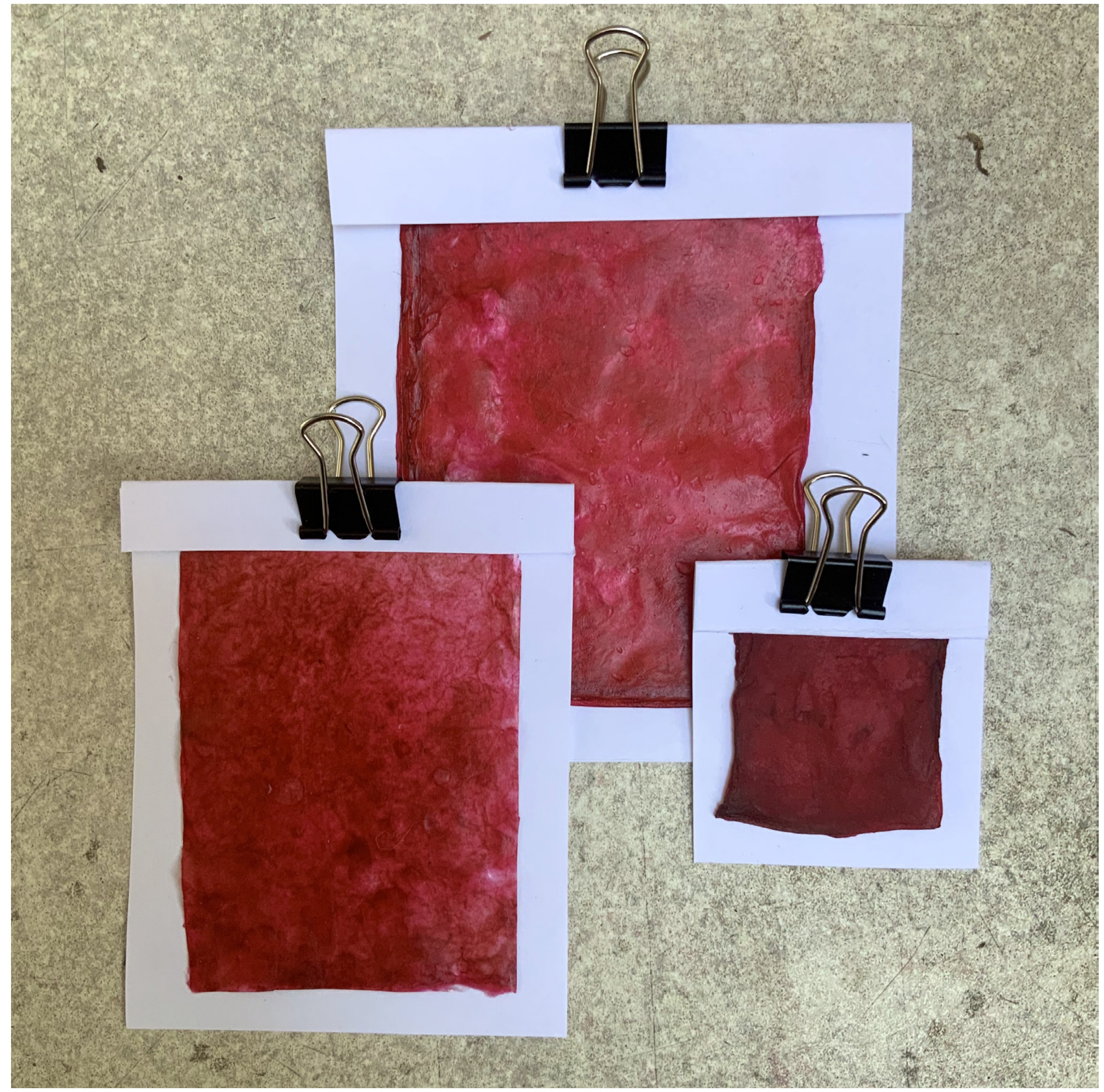
Tannins

Tannins are contained in beverages as tea or coffee, and are a good support for microbial growth.

In the basic kombucha tea recipe is possible to substitute fresh tea with tea waste, not good for drinking anymore but still able to release useful substances.

Also coffe grounds are a valuable fermentation medium and can be used in different ways: in powdered form they create a surface texture without colouring the material, however the best way is use them for a second coffee brewing to get a liqid dye.





Red Cabbage

As bueberries red cabbage cointains anthocyanins, therefore in the acidic environment required for scoby fermentation will result in a similar colour palette.

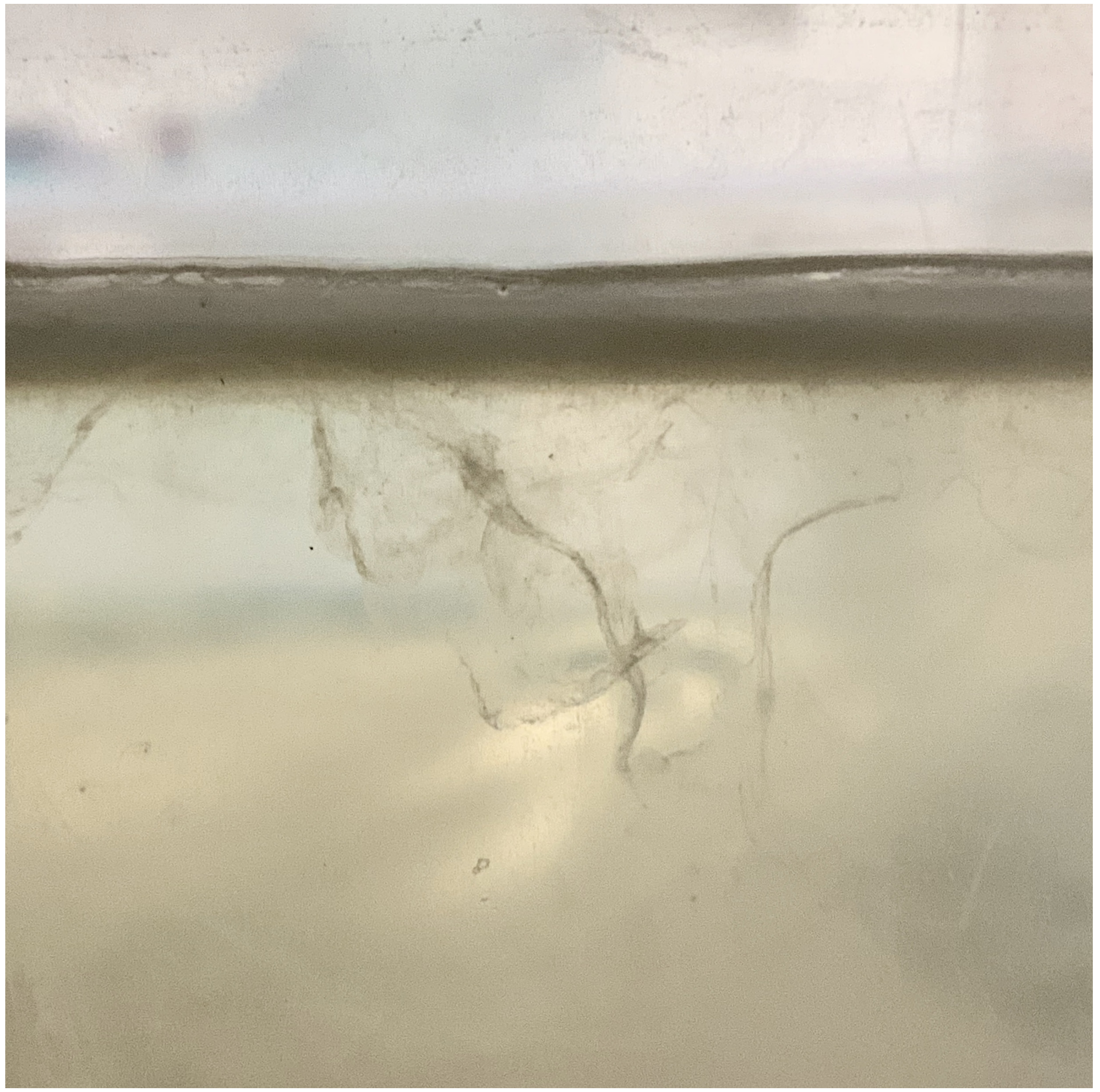
As vantage point, red cabbage dye can be upcycled from food industry waste. Conversely however, it has a strong unpleasant smell while blueberry dye gives the material a more delicate and sweet smell.

colour & smell

Acting on food sources affects also the perceptual qualities of the material produced, such as colour, smell and texture. The experiments then, continued investigating the possible range of the colour palette with which microbial cellulose can be produced. The growth takes places in an acidic environment with a pH that ranges between 2.5 and 3.5. For this reason cellulose will grow within a specific colour spectrum which includes browns, yellows, reds, pinks and purples, while "colder" colours such as green, blue or violet cannot be obtained during the growth since they usually require alkaline or neutral environmental conditions. Using coloured food sources in different concentrations is possible to get a variety of colours and hues, from intense and saturated to pale and tending to transparency.

Besides exploring the colour spectrum, part of the experiments focused on the possibility to produce white-transparent nanocellulose. For this purpose vegetable milk, such as rice or coconut milk, resulted to be a valid growth medium, providing sugars and producing an almost transparent, pale-white translucent material. Even water can be used as liquid growth medium, to produce transparent nanocellulose, however the lack of additional elements useful for the fermentation process makes the growth extremely slow and the final cellulose layer too thin to be dryed, requiring stratification or folding to get an appropriate thickness.

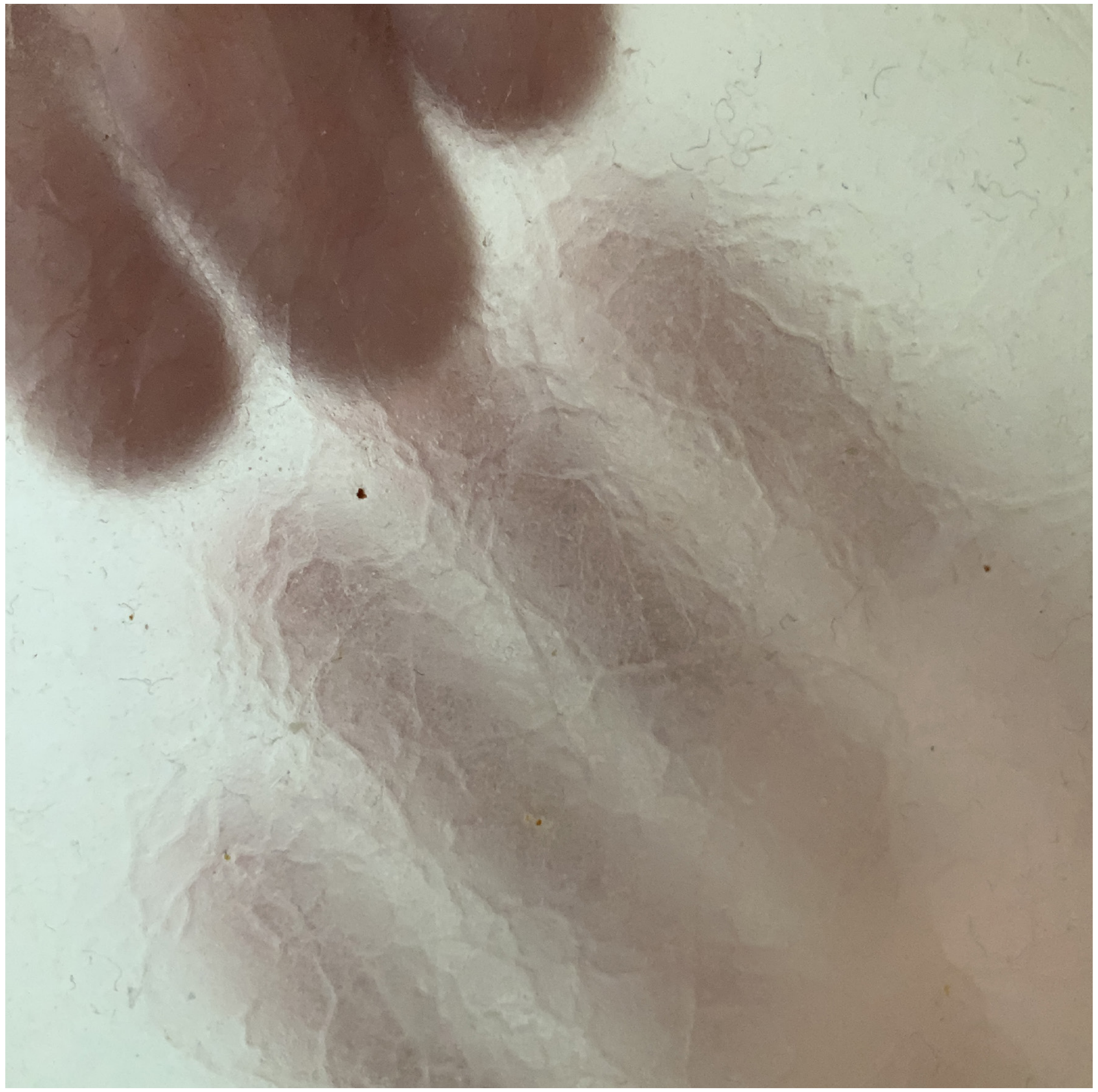
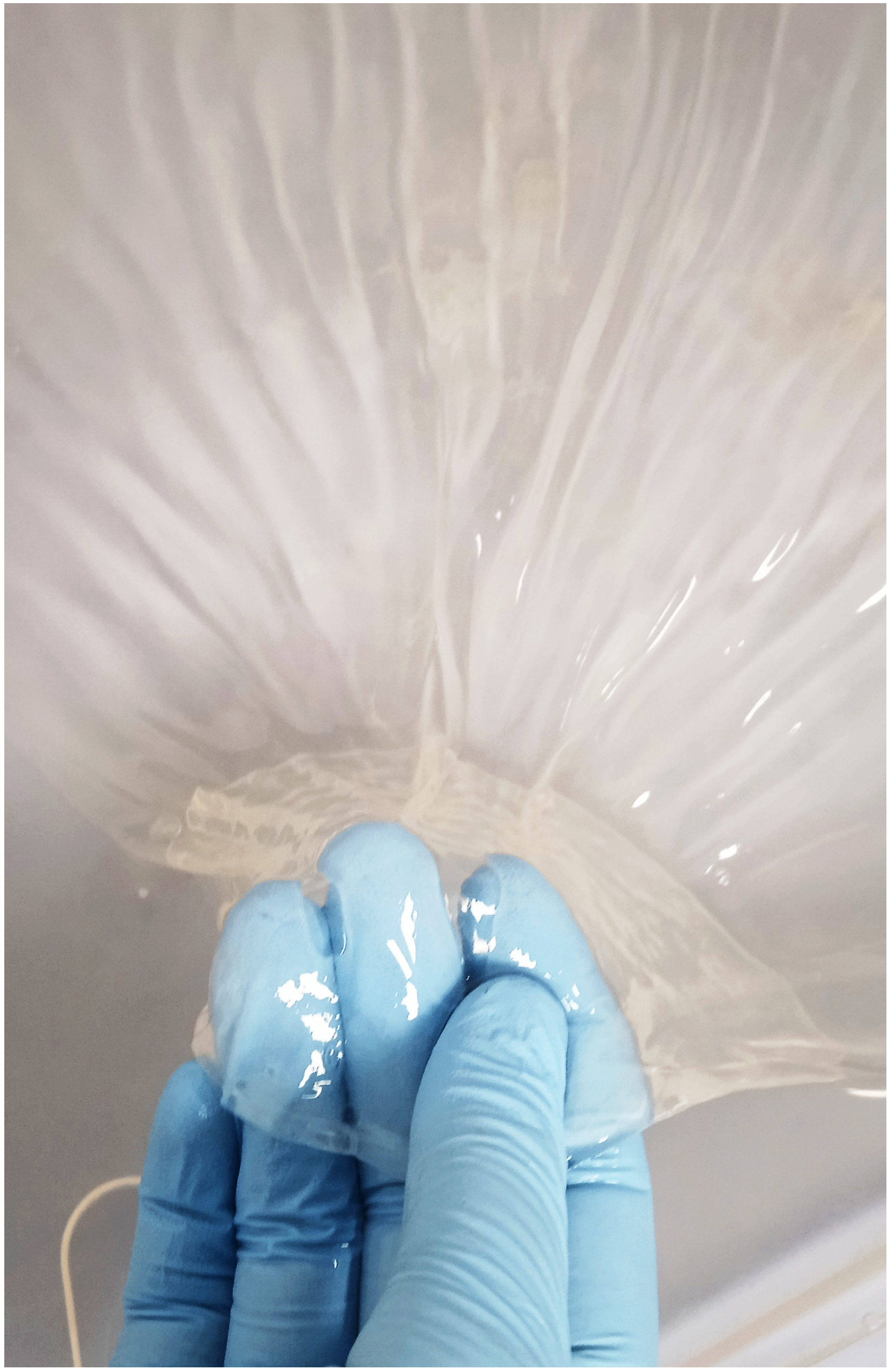
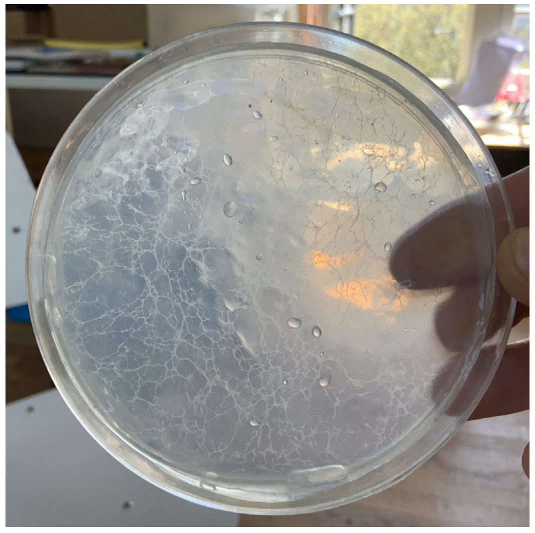
Changing the kind of nutrients with which feeding the culture affects the colour of the material, but at the same time also its smell. This represents one of the boundary conditions through which we can affect and control the microbial growth and therefore the material properties: we don't have the possibility to radically eliminate the strong acidic smell from the material, but we can intervene to modify it, making it sweeter through sweet-smelling fruits, less intense and acidic with coffee, or even stronger as happens with fermented wine.



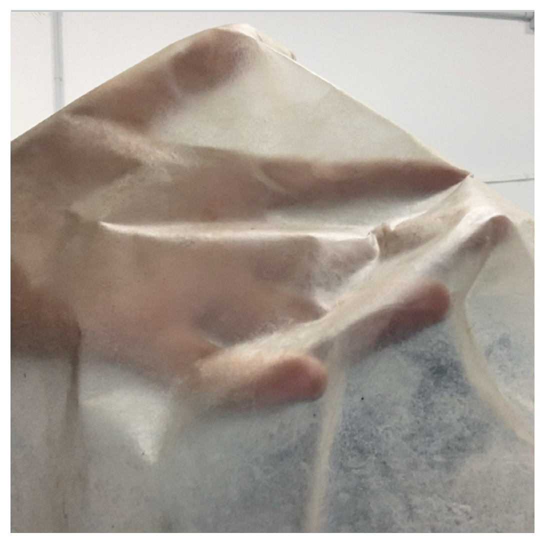
White and Transparency

Reducing the amount of tea in the culture medium till the point of using just water is possible to obtain increasingly transparent nanocellulose sheets.

However, with pure water the growth happens at a very slow rate, producing thin layers. Is possible to increase the thickness of the material exploiting its self-bonding properties, and then folding or stratifying when still wet.



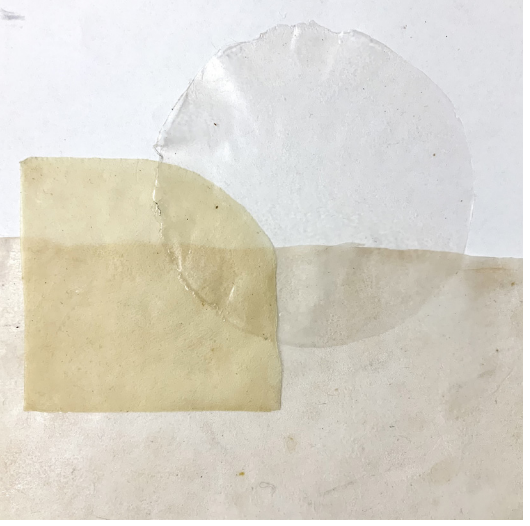



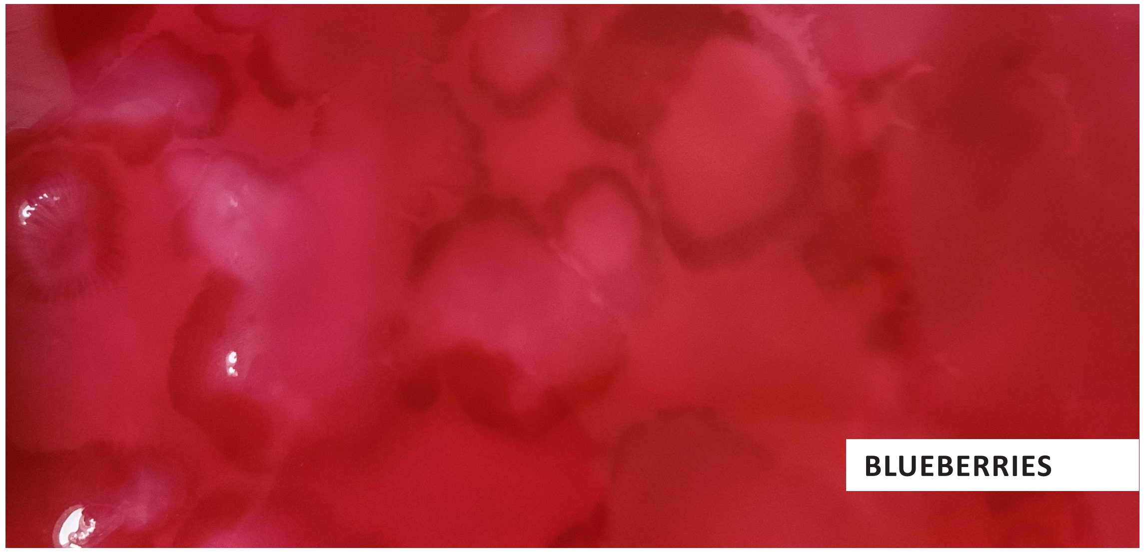

White and Transparency

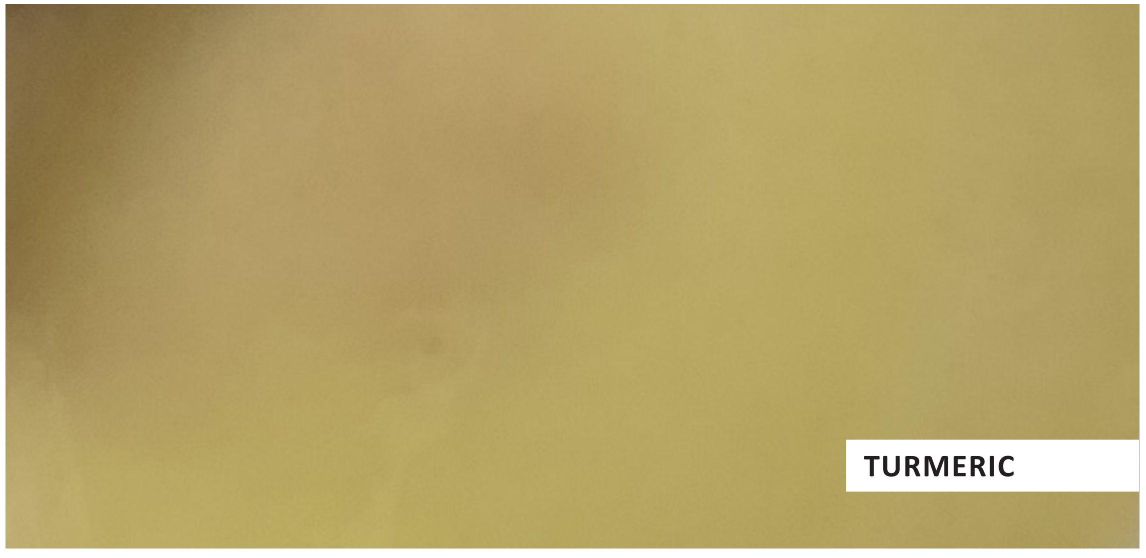
Another good food source useful to produce white nanocellulose are vegetable milks.

The samples in this page are fabricated using Rice Milk as culture medium which, differently from water, naturally contains sugars and therefore can grow quicker and better.

The resulting material will be whiter than the one produced with water, and more opaque.





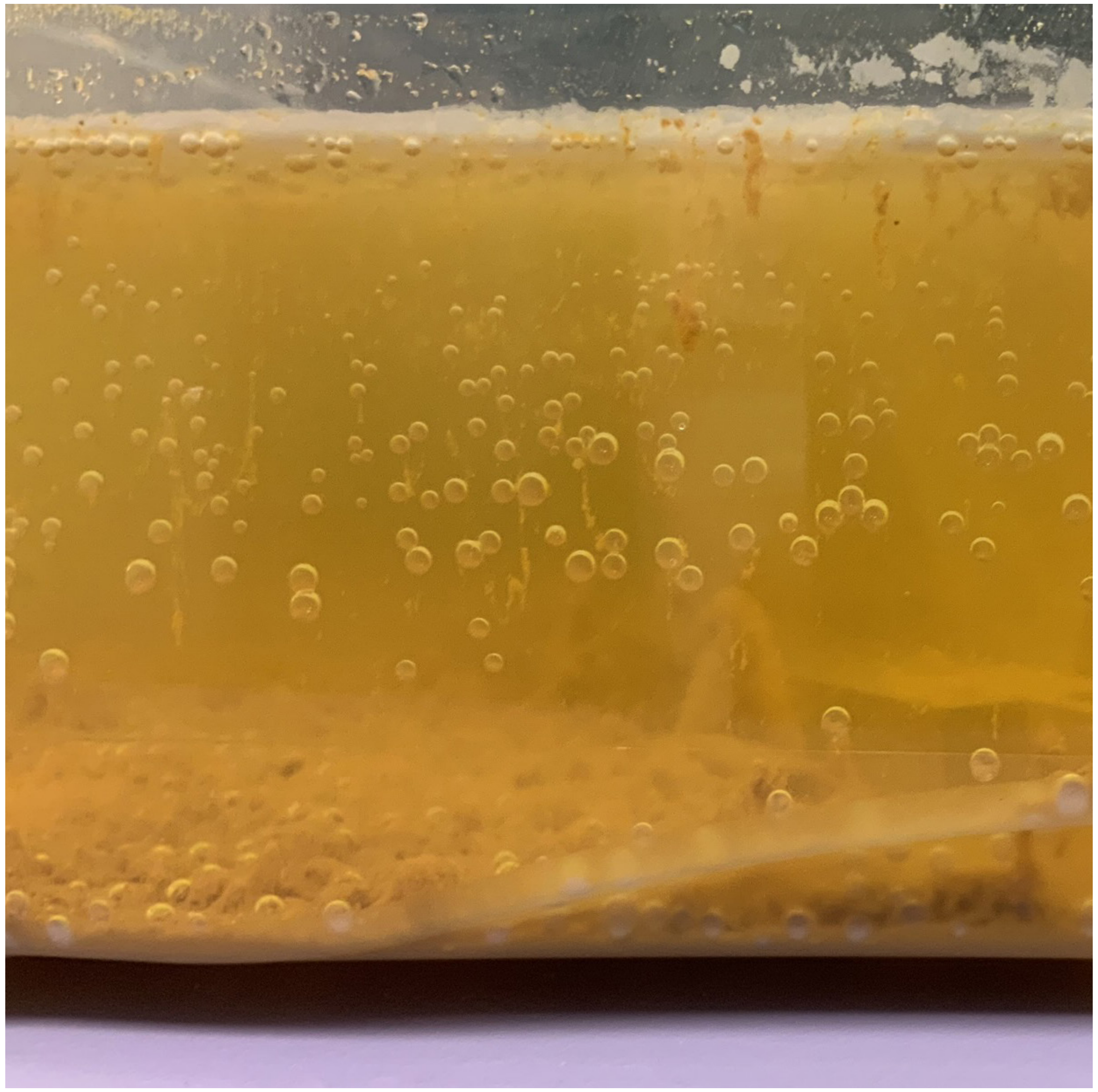


texture

Besides environmental factors as temperature and humidity, the amount of food available can boost the growth rate. Cultures with higher amounts of nutrients (in the form of sugars or ethanol) will therefore result in higher growth rates. However, the velocity of the fermentation process determines also the way the cellulose nano-filaments are layered above the liquid surface, determining the structure of the material and therefore its texture and mechanical properties.

A fermentation process that happens too fast can result in the formation of air bubbles in the cellulose layer, producing holes or variable thicknesses and generally a weaker material. Another unwanted consequence can be the irregular distribution of the filaments that will be concentrated in certain random spots while leaving a very thin layer all around them. When such variations are slight they can create a unique texture on the material surface, whereas when they are significant can invalidate the succes of the experiment.

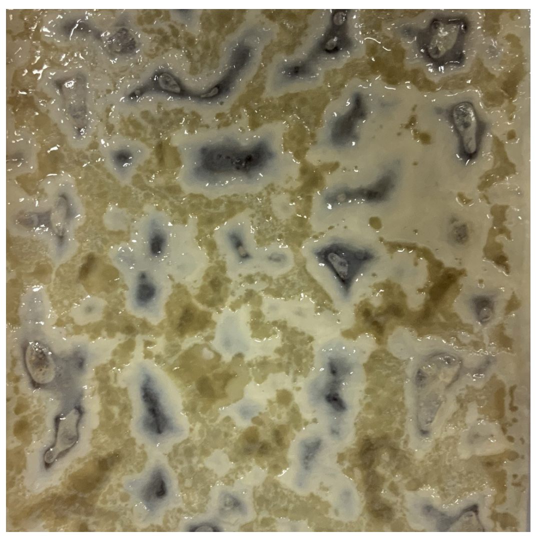
Another factor which can affect the texture is the use of powdered pigments instead of liquid dyes. If it is a proper food source the powdered pigment is able to colour the material in the same way of the liquid dye, since it is eaten by the microbes who will produce coloured nanocellulose filaments. On the contrary, if it doesn't represent a food source the powder won't affect the growth and will deposit on the bottom of the container. That's not always true because when the pigment used is a very fine lightweight powder, as in the case of charcoal or spirulina, it will float in the culture liquid getting tangled up in the nanofilaments. In this way, despite not colouring the main cellulose layer, the pigment is embedded on the material surface creating an organic coloured texture.

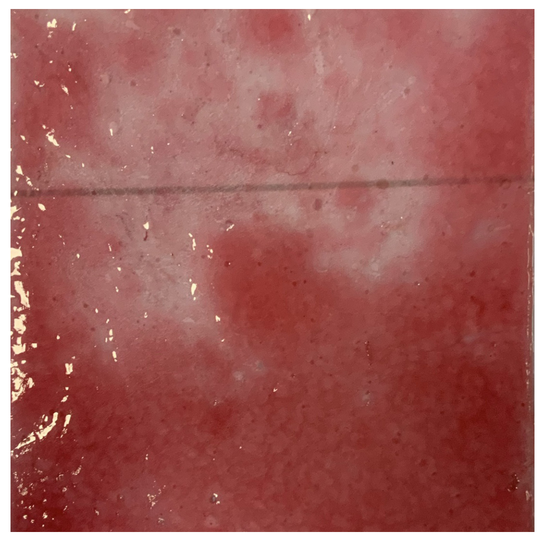


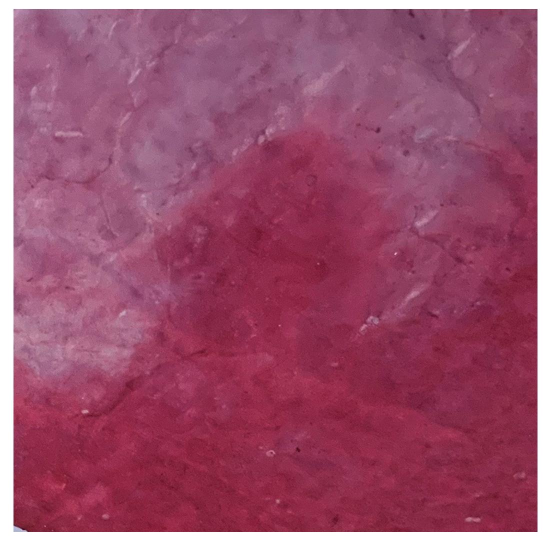
Air Bubbles

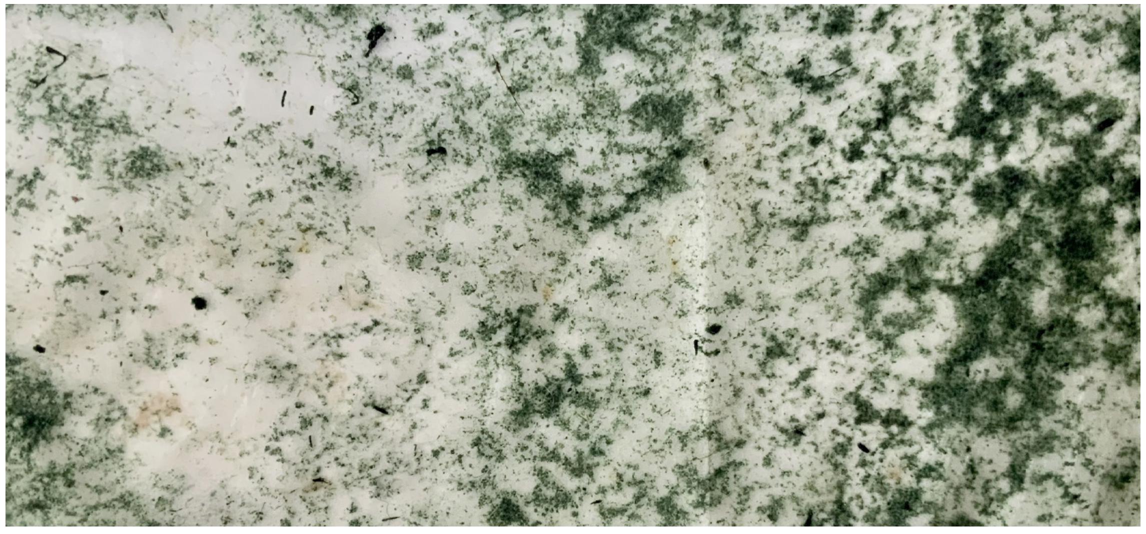
A fermentation process which happens too rapidly can cause the formation of air bubbles which will affect the stratification of nanofilaments during the growth.

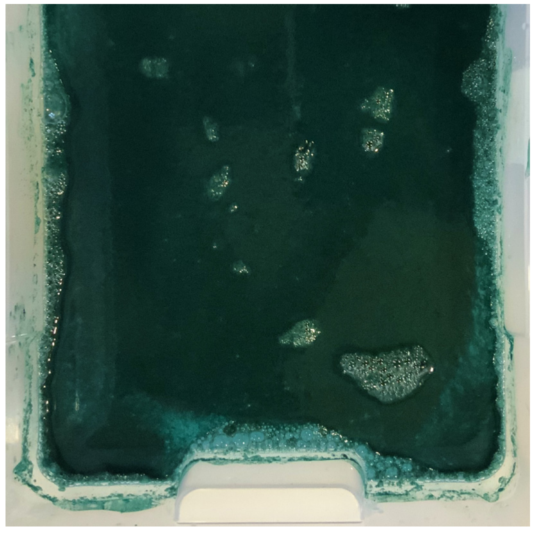
They can be large bubbles that will detach the cellulose layer in some spots preventing the growth in that areas, or smaller ones which will prevent the appropriate nanofilaments bonding, resulting then in a weak material.







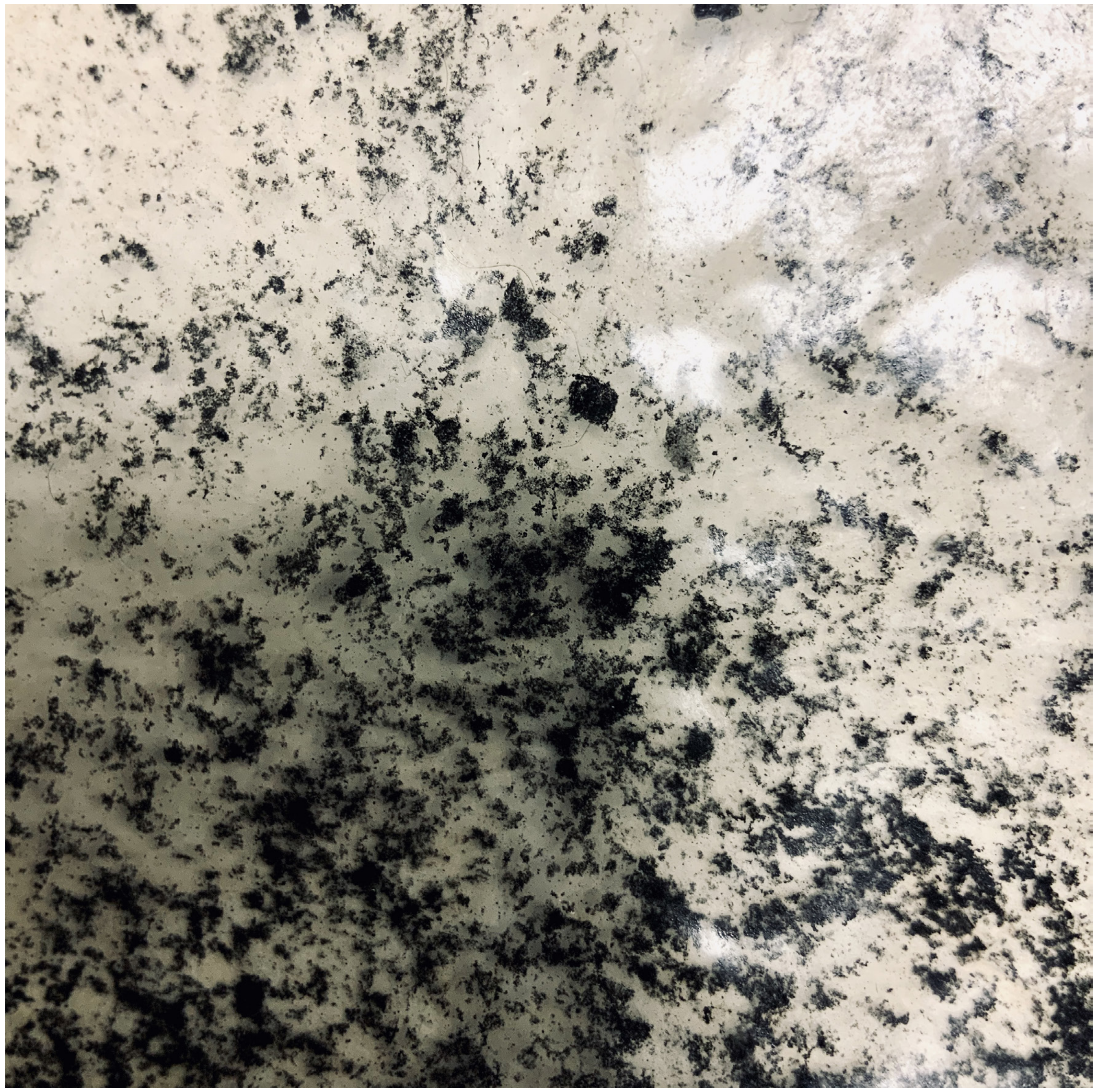


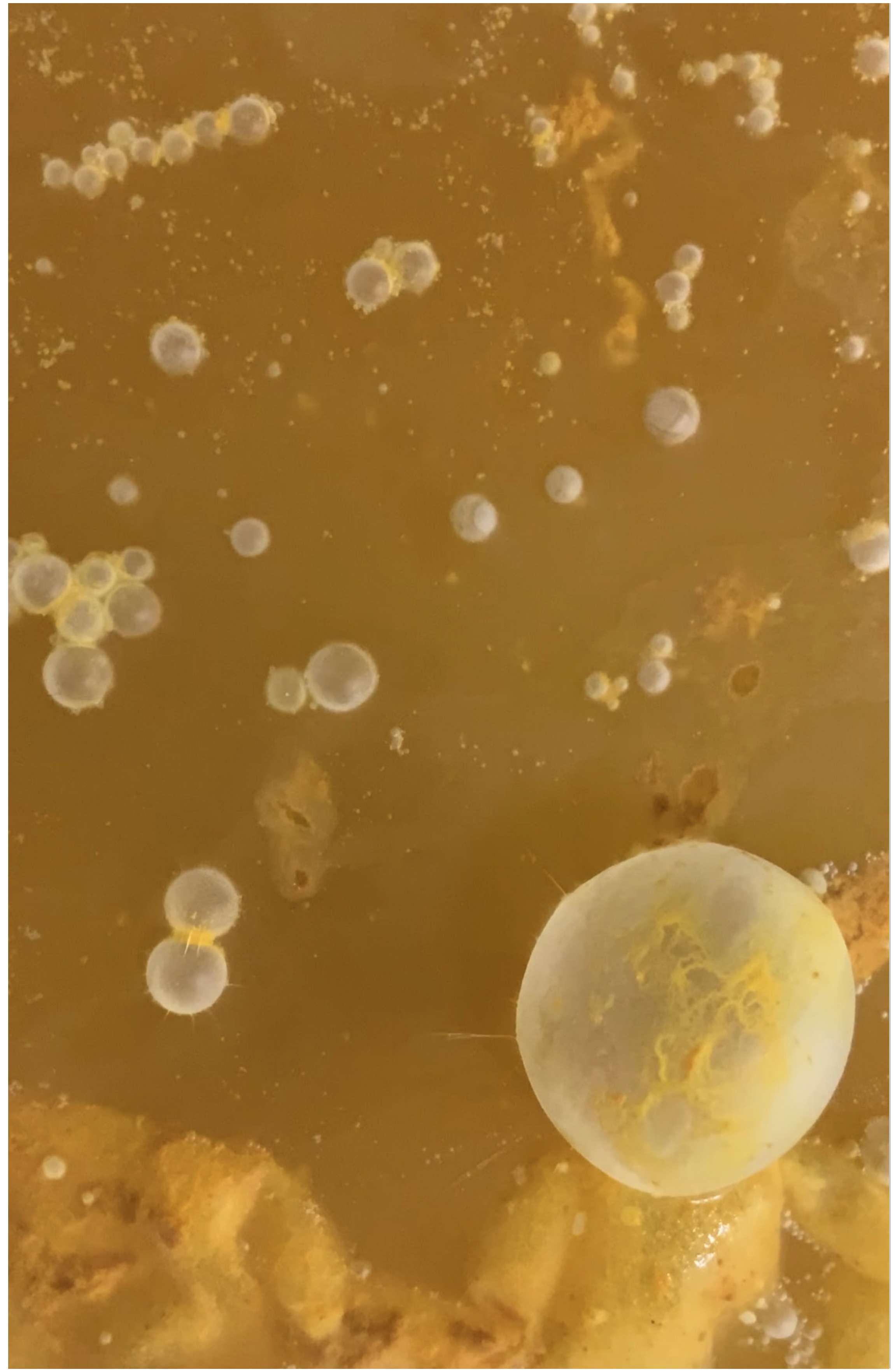


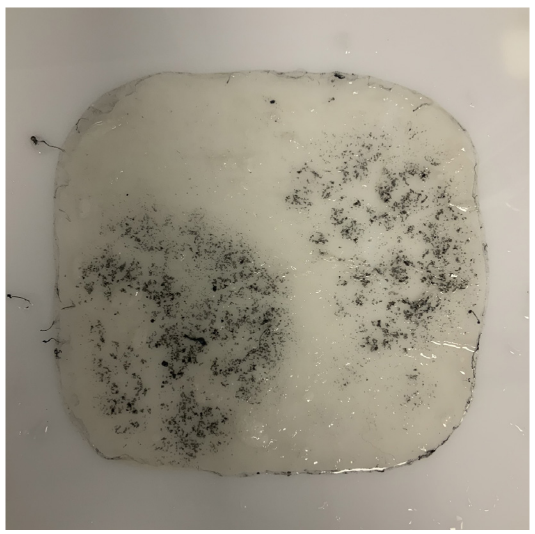
Powdered Pigment Texture

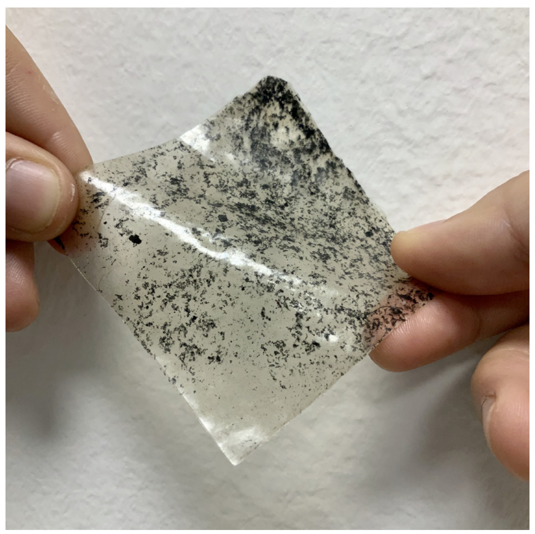
Thin powders as spirulina or charcoal can be added to the culture medium.

While floating in the liquid because of their light weight, they get trapped by the nanofilaments rising to the surface and are then embedded on the cellulose bottom surface creating random surface textures.









Controlled Growth

Microbiology Laboratory Tests

The experimentation on microbial nanocellulose involved a set of laboratory experiments carried out in collaboration with Emily Schifano PhD and Prof. Daniela Uccelletti from Biology and Biotechnology Department Charles Darwin of Sapienza University, who made available their facilities and skills.
In this case the growth protocols, unlike the other experiments described in this thesis, took place in a sterile and controlled environment. This made possible to manage and intervene on environmental conditions such as temperature, light, humidity, etc., but especially to prevent from any external contamination since working under a fume hood. Such conditions made possible to examine each parameter one by one and, excluding environmental factors, accurately understand which variations will result in a stronger and faster growth.

The experiments were made using the basic growth protocol which involves the use of tea as culture medium, and acted through separate experiments on several parameters as follows.

- *pH variations* - from 2.8 to 4.8
best result: **pH 2.8**

- *typology and amount of sugar* - saccharose/glucose
best result: **glucose at 6.5%**
[26g on 400 ml of total volume]

- *temperature variations* - from 25 to 28°C
best result: **28°C**

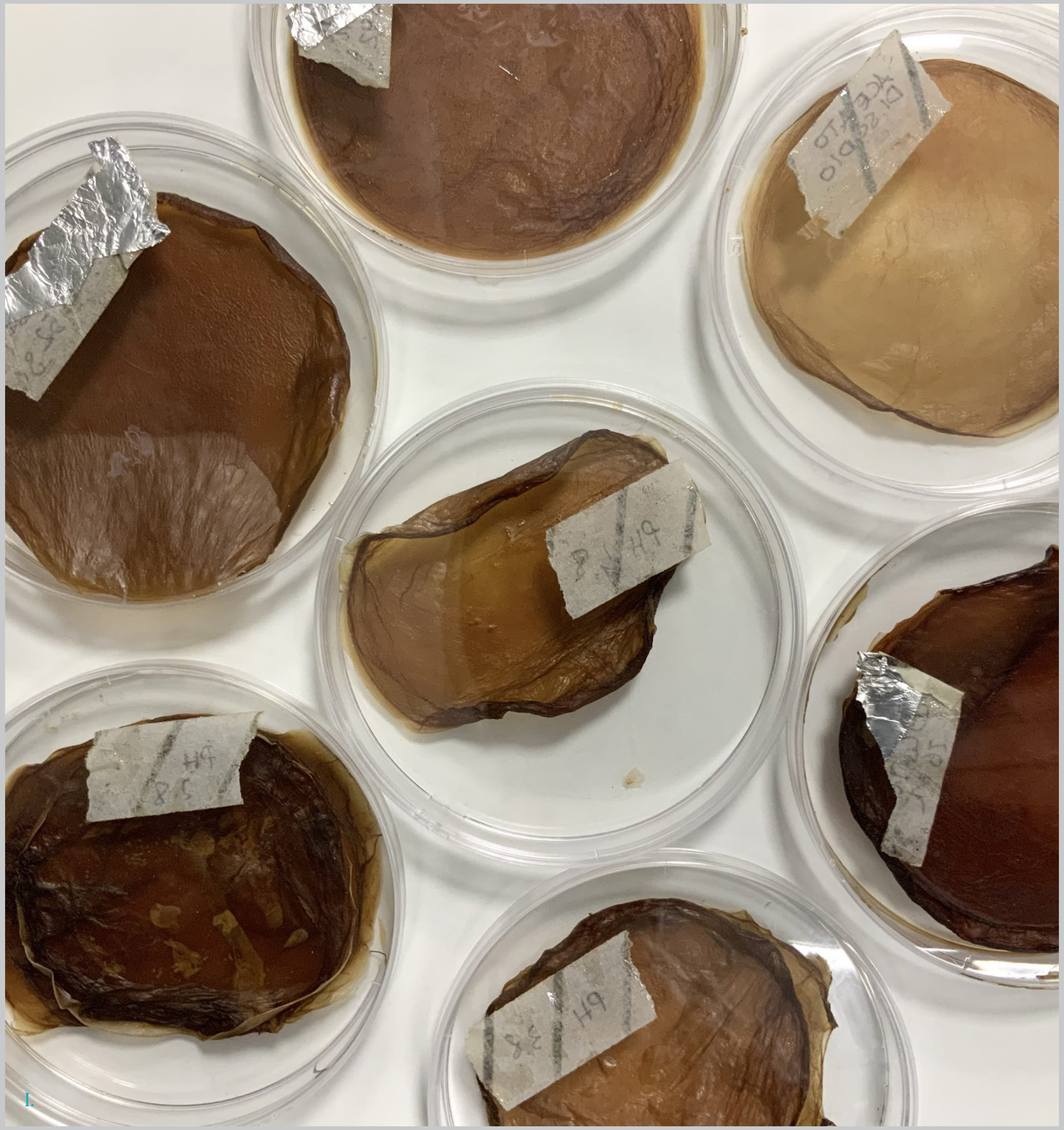
- *dark vs. lit environment*
best result: **dark**

- *liquid vs. solid scoby starter*
best result: **solid starter**

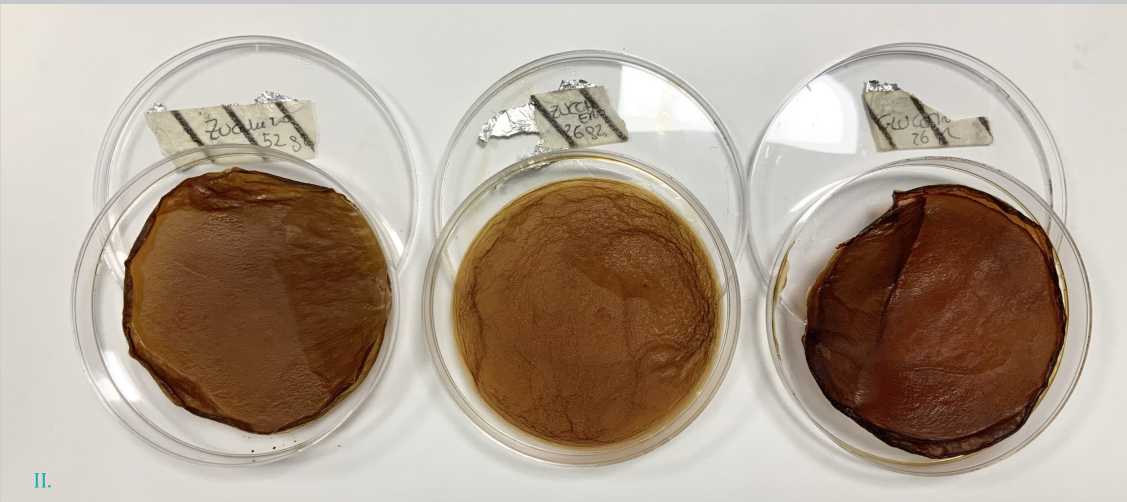
- *solid starter amount* - from 1x to 8x
results: **minor differences** among the resulting materials, no relevant impact

Working in collaboration with scientists takes the material experimentation to a whole new level, making it possible to gain an adequate degree of control over the fermentation process. This is essential in order to move from the experimental research stage and reach real-life implementation.

Moreover, the two apparently opposite approaches towards biofabrication are instead complementary, and able to trigger reflections and ideas which are the result of the encounter between the designer and the scientist mindset, and wouldn't be possible without this interaction and contamination. Once again, transdisciplinary collaboration appears to be the only way to effectively tackle contemporary issues, which complexity cannot be faced by individuals nor by fragmenting it into sub-issues independent from each other, but requires multiple skills and collective action.



I. Microbial nanocellulose samples with different pH values, oven dried. Produced in the Department of Biology and Biotechnology of Sapienza University in collaboration with E. Shifano PhD and Prof. D. Uccelletti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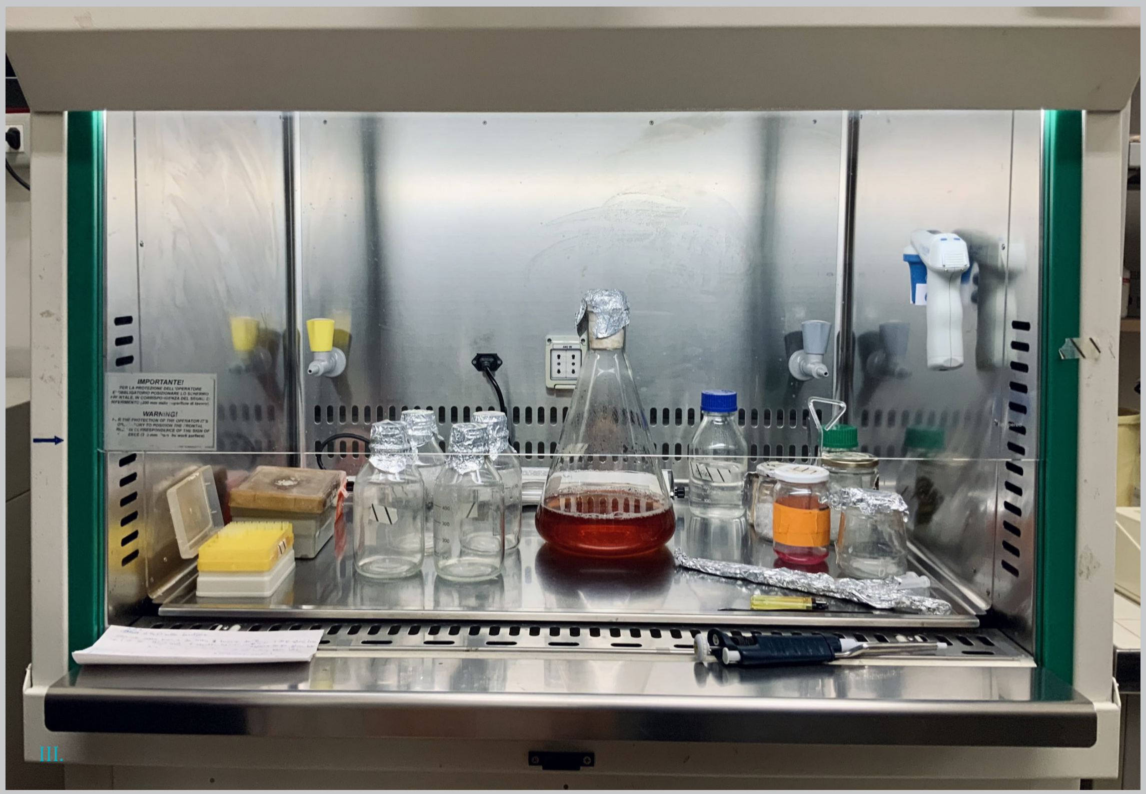
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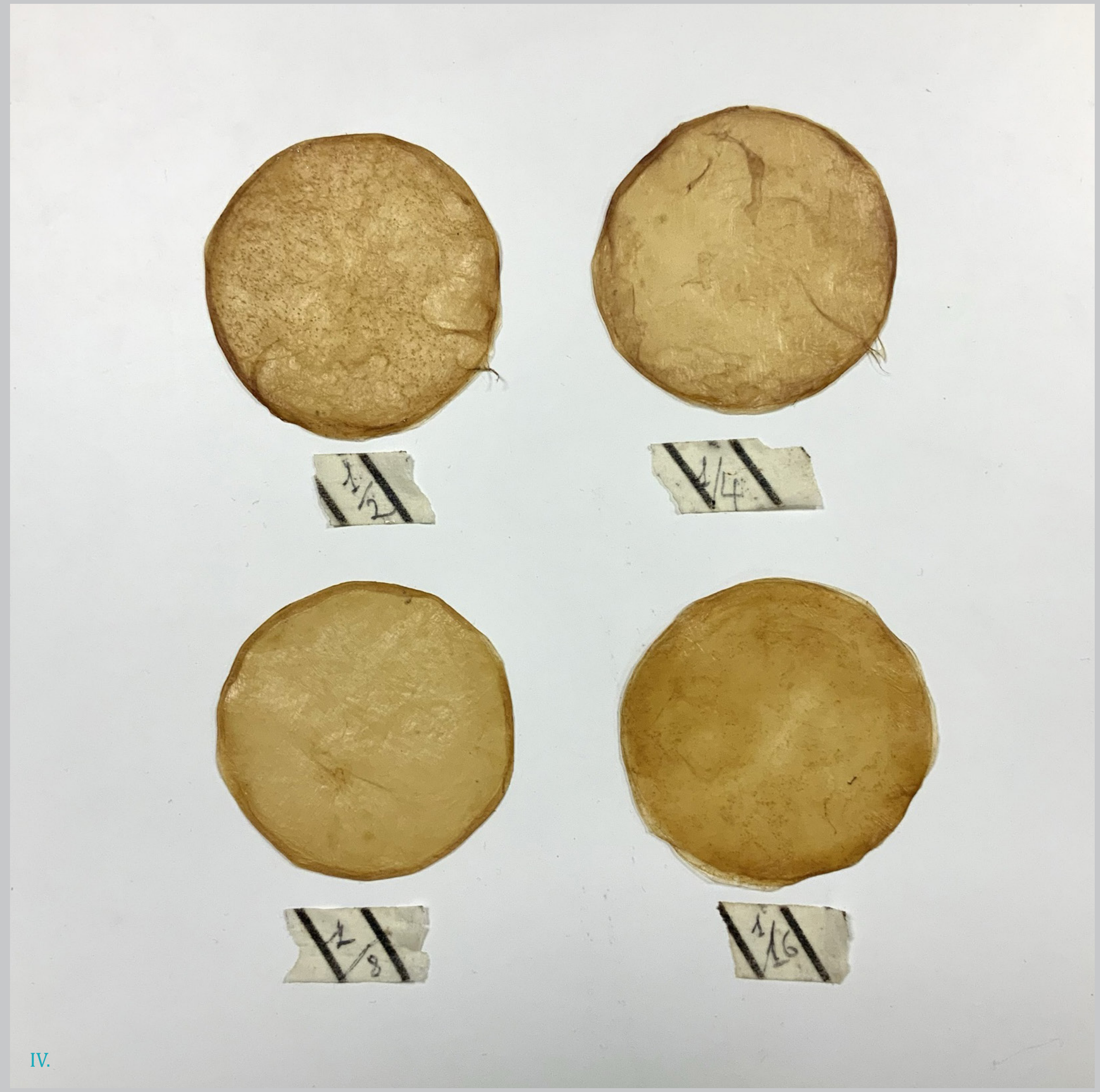
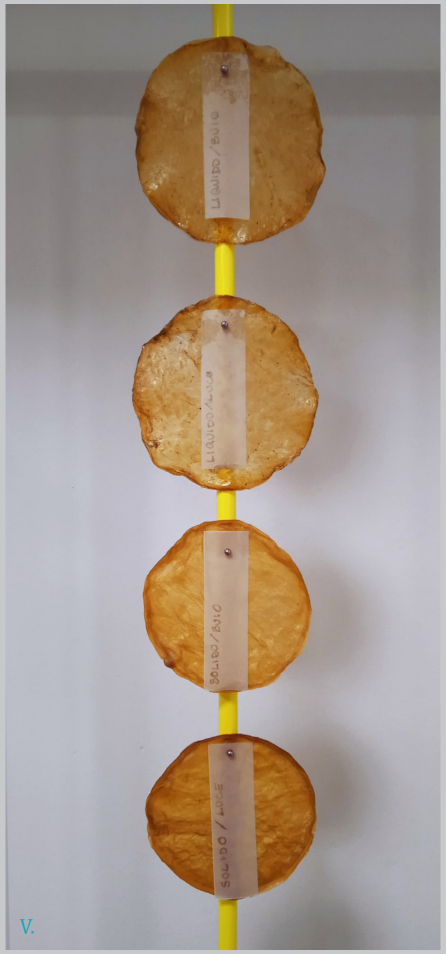


IV.

II. Microbial nanocellulose samples with different types and amounts of sugars, oven dried
III. Sterile workspace: fume hood. Department of Biology and Biotechnology of Sapienza University
IV. Microbial nanocellulose samples with different amounts of SCOBY starter



V.

VI.

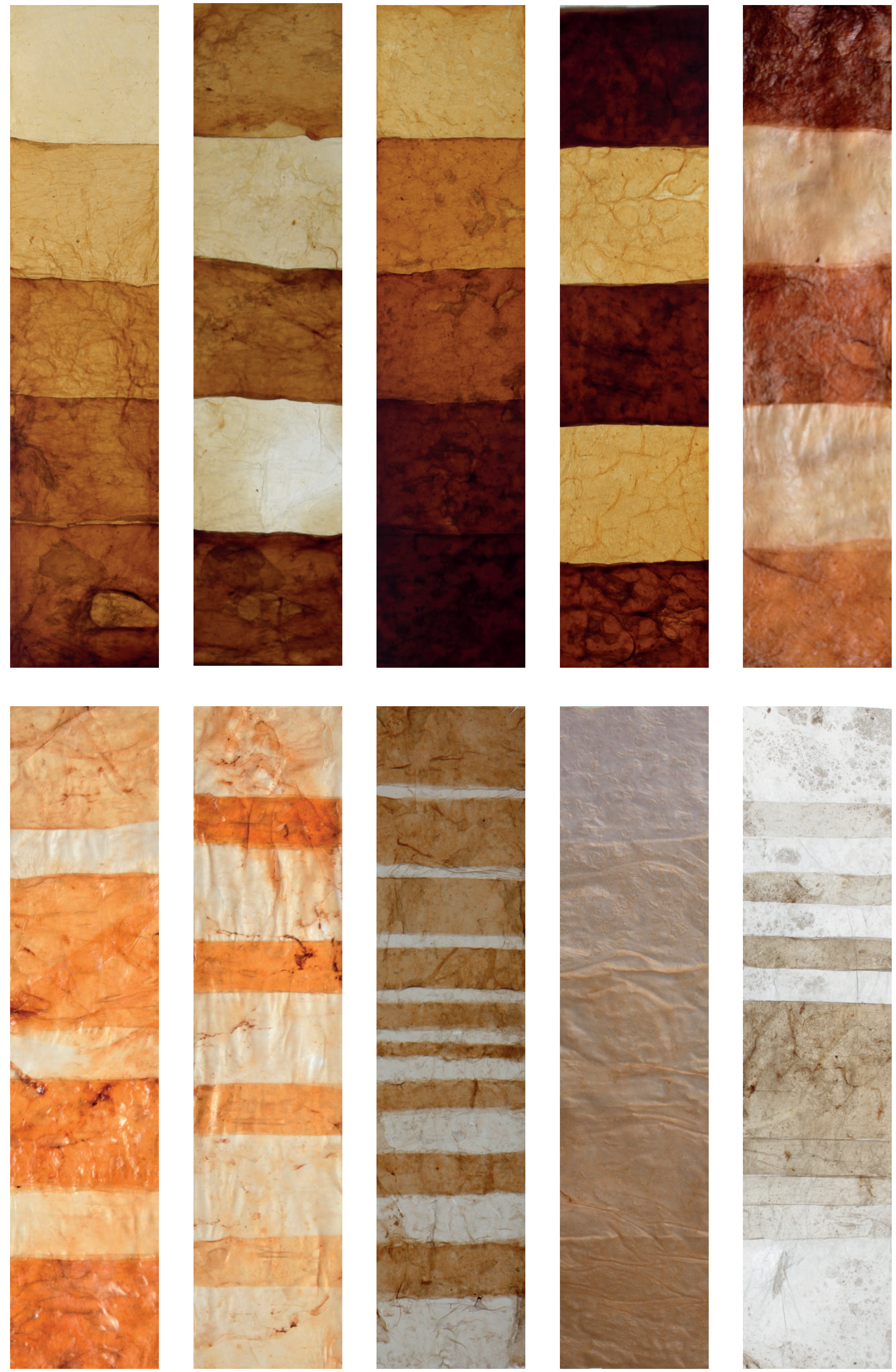
V. Microbial nanocellulose samples grown in different environmental conditions (light/dark) both with solid and liquid starter, air dryed
VI. SCOBY cultures fermented in different environmental conditions (light/dark) both with solid and liquid starter

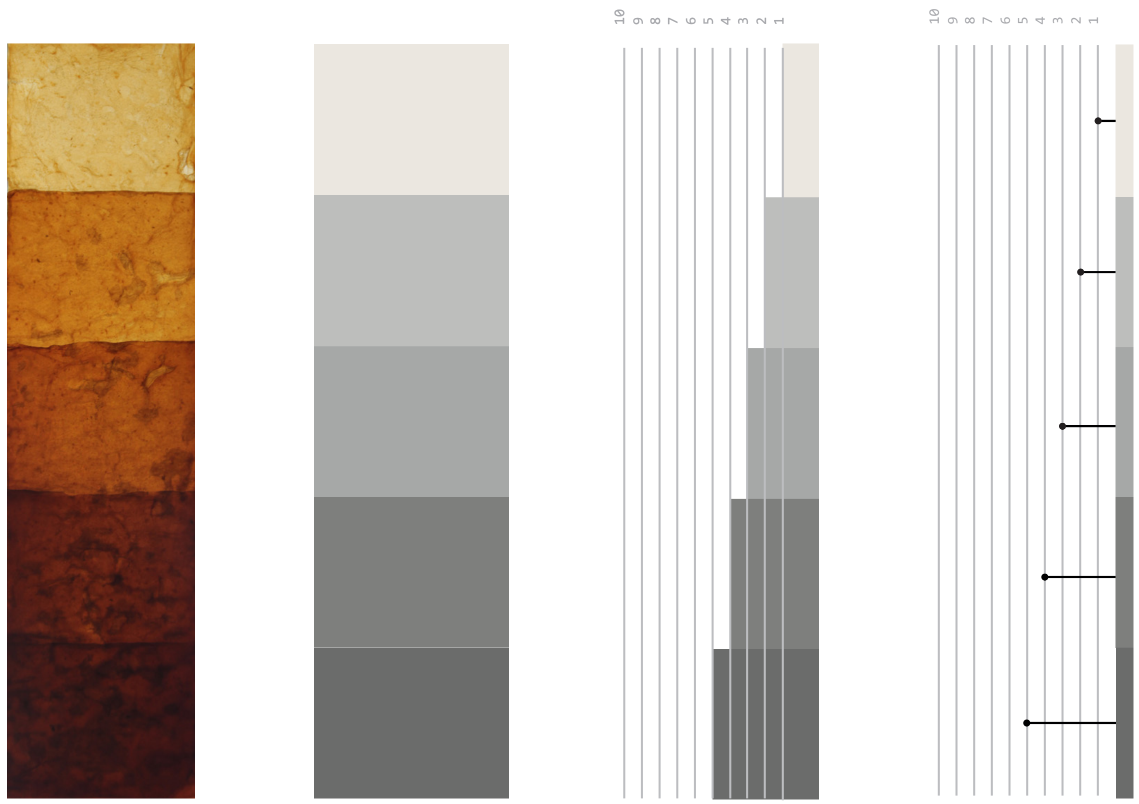
6.2.2. Processing

Apart from interacting with the growth process in order to modify and calibrate the aesthetic-perceptual aspects of microbial cellulose, is also possible to interact with the grown material when still wet after the harvest stage, as well as when already dry.
This stage of the hands-on experimentation includes tinkering and manipulation activities on the material which will contribute to build and develop experiential knowledge about it, through the observation of its behaviour when subjected to certain sollicitations or processing. Thereby this will makes us understand how to handle and manipulate it, what it can do and what not, and which techniques, tools and utensils are more suitable for its manufacturing, unveiling one piece at a time its identity as material.
In doing so we will sometimes insert into existing processes reinterptreting them through new perspectives, contaminating and hybridising traditional techniques and material innovation.

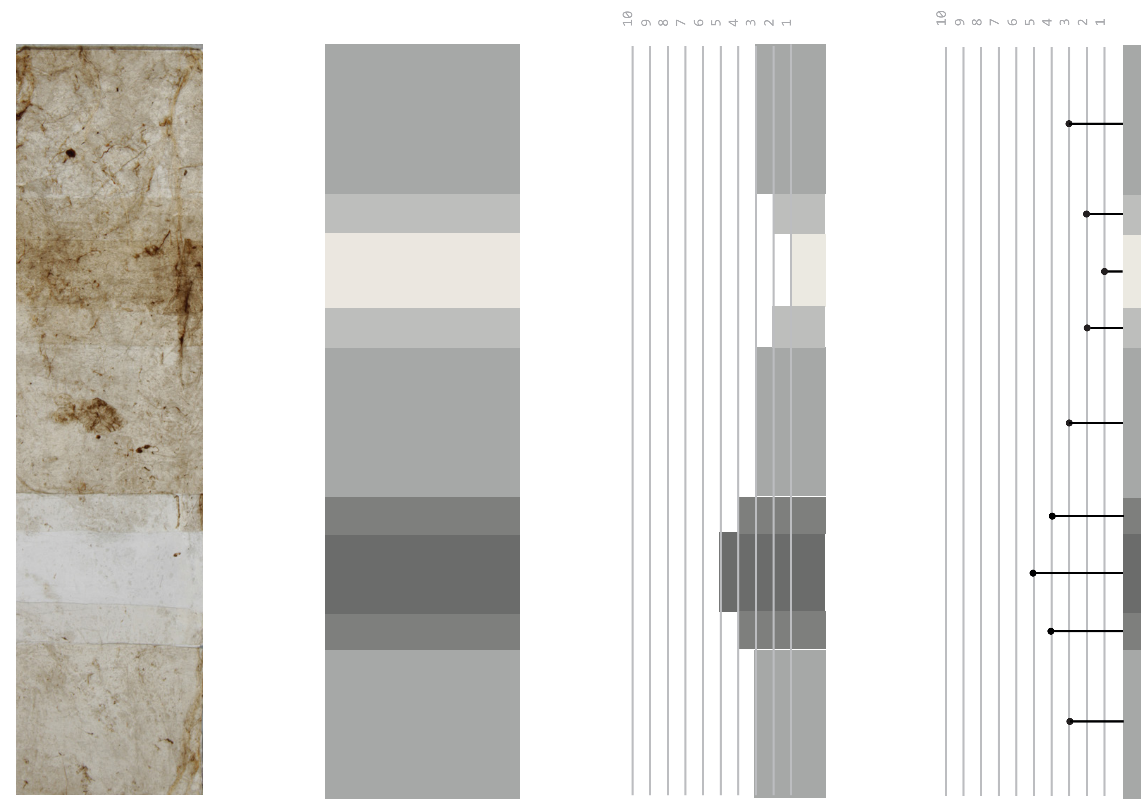
· wet > **stratification**

When harvested, the wet material is like a spongy mat full of liquid culture. While drying it releases and let evaporate all the liquid inside, shrinking in thickness. During this process the nanocellulose filaments bind together creating a strong unique layer, sealing any cut or small hole in the meantime. This ability to "self-seal" and stick together can be used for stratification. In this way is possible first of all to gain a better control on the final material, having the possibility to adjust the thickness also after the growth overlapping thinner cellulose layers. Moreover, since the microbial cellulose is translucent, this technique can be used to control and modify the transparency of the material –the thicker it is, the duller and darker is its colour.

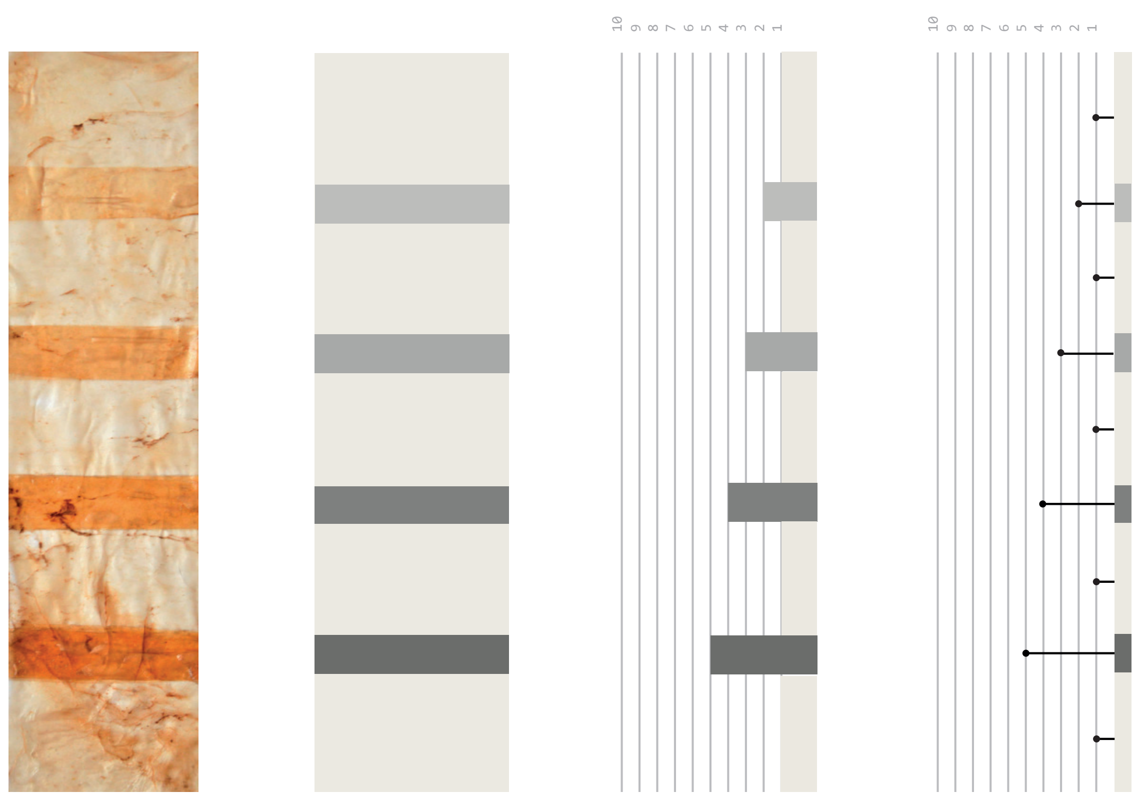




Transparent-Opaque / table 25



Transparent-Opaque / table 28



Transparent-Opaque / table 19

Sensory Scales

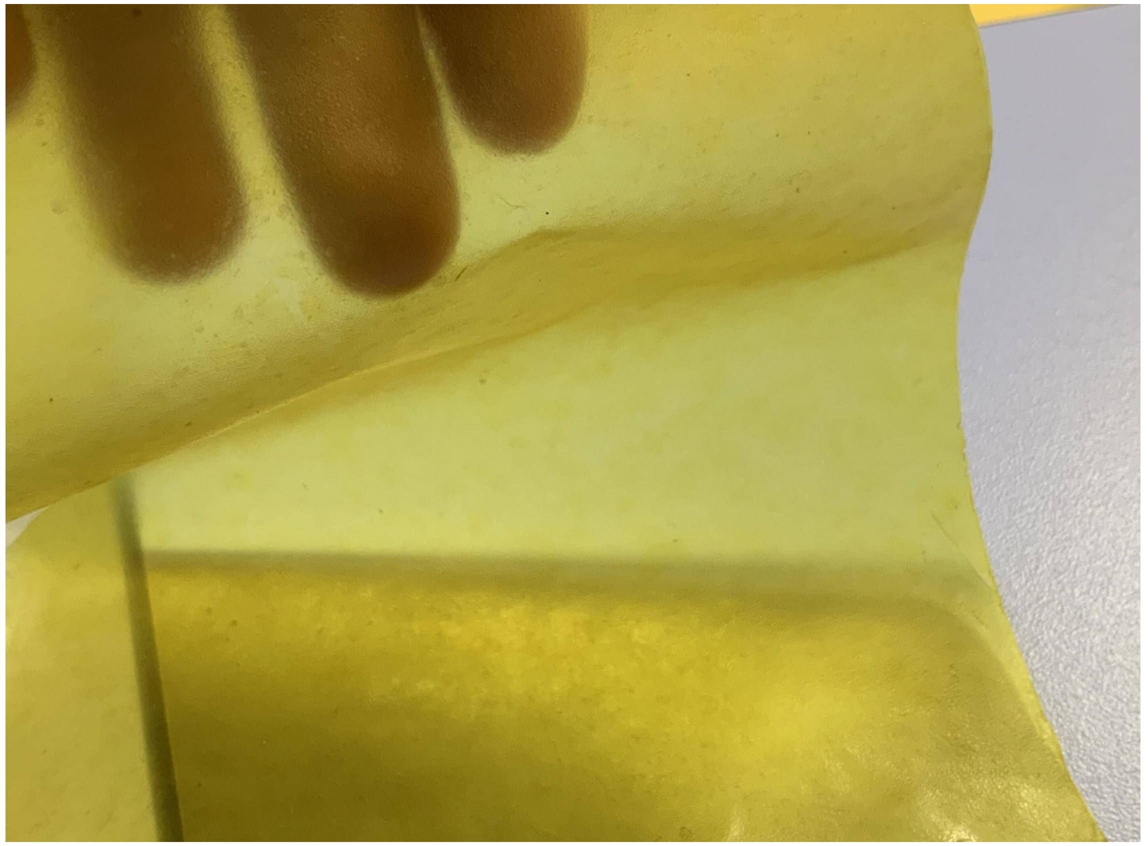
Thesis work by Maira Campanella, Laura Laricchiuta and Camilla Summa from Politecnico di Bari, in collaboration with Inmatex research lab.

First supervisor Prof. Rossana Carullo, second supervisor Prof. Sabrina Lucibello, co-supervisors Giuseppe Modeo, Mariangela Stoppa and Lorena Trebbi.

The scales are both visual and tactile: different thickness entails different colour, transparency but also flexibility and resistance of the material.

Opacity increases proportionally to the number of layers, and the same happes for colours which become more and more intense and saturated as the thickness increases.

2. Sensory Scale made alternating Paper and Microbial Cellulose



· wet > **texture and moulding**

The final morphology of the material will be obtained after the drying phase, since it can be still shaped while wet. Placing it on an embossed surface while drying is possible to create folds, plisse, bumps, and even 3d shapes. Adittionally, it is possible to imprint any texture on the material changing the flat surface used for the drying stage, since its surface texture will be transferred to the material surface. Extremely smooth plastics such as acrylic panels will result in a glossy finish, while rougher surfaces such as polypropylene, styrofoam or wood will result in a matte and more "natural" skin-like texture.

· wet > **composites**

Microbial cellulose can be also turned into a pulp and mixed to other materials to create bio-composites. Blending the nano-cellulose layer however, means to break down all the nano filaments into smaller parts as happens for paper recycling, resulting in a weaker material with a lower tensile strength. The cellulose pulp can be used as a binder to make composites out of waste – with tea leaves, coffee grounds, etc –, or as basic component of the composite to which additives can impart new properties.

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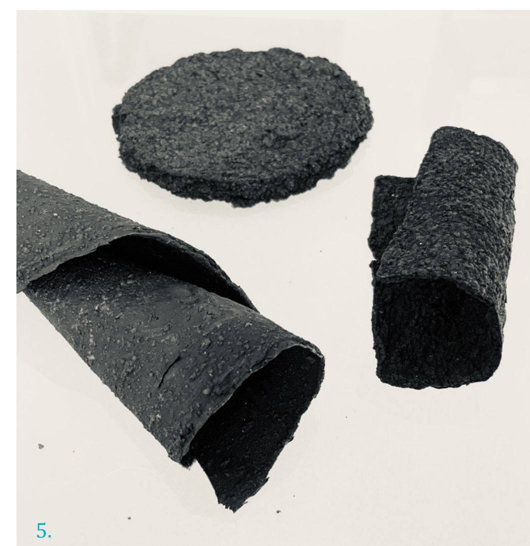

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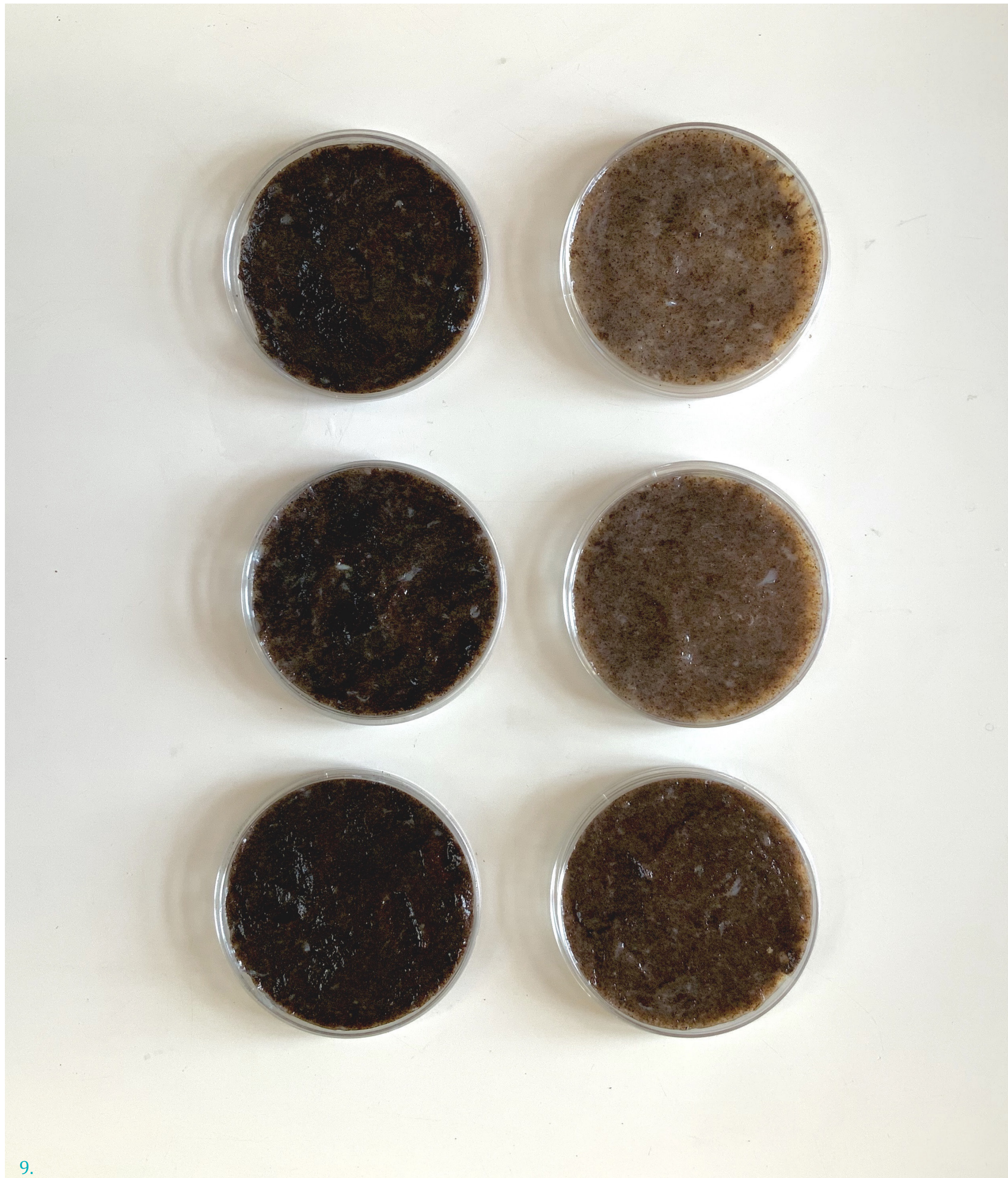

9.


10.


11.

coffee composites:

6-8. Production stages

9. Microbial cellulose and Coffee grounds composites: varying proportions, wet samples

10-11. Microbial cellulose and Coffee grounds composites: dry samples. Varying the proportion between the two components will determine material samples wich go from completely opaque to translucent when illuminated

previous page:

3. Microbial nanocellulose composites: cardboard, charcoal, alginate

4. Microbial nanocellulose composites: tea waste

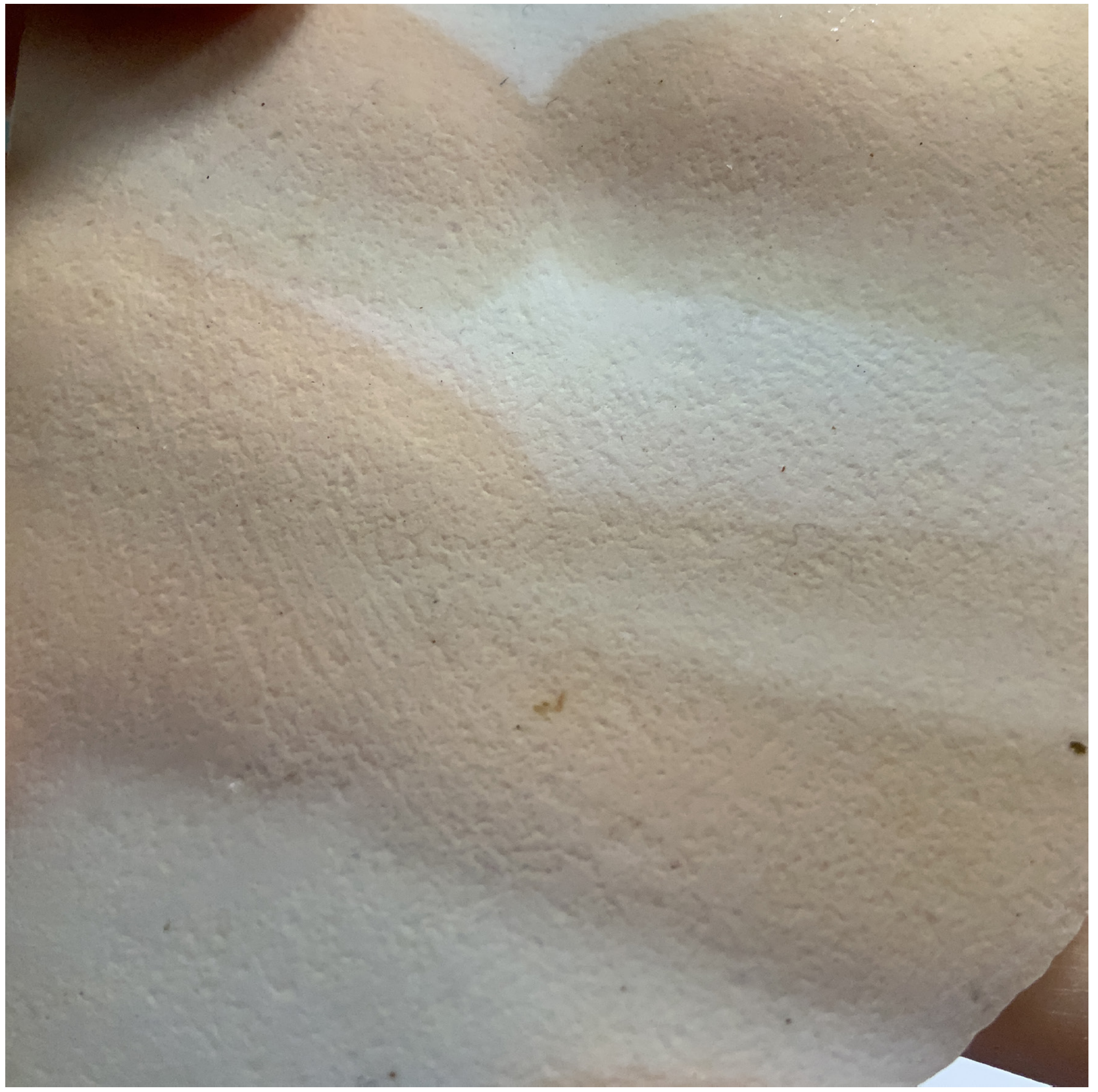
5. Microbial nanocellulose composites: charcoal, different grain size

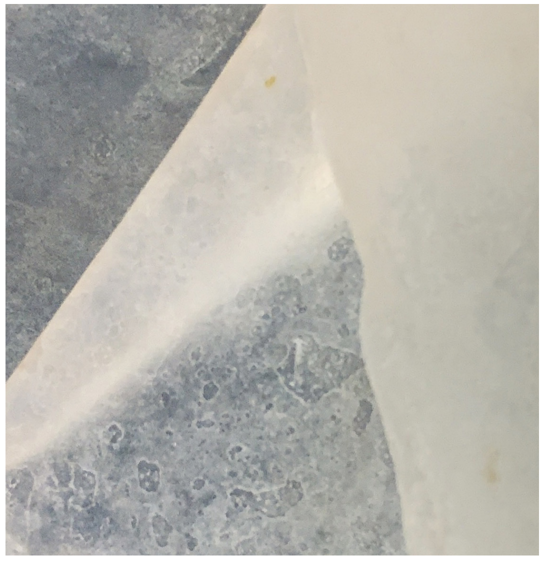
· dry > **absorption**

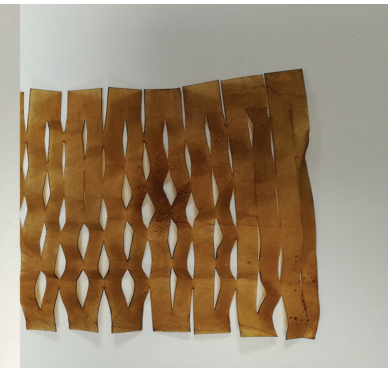
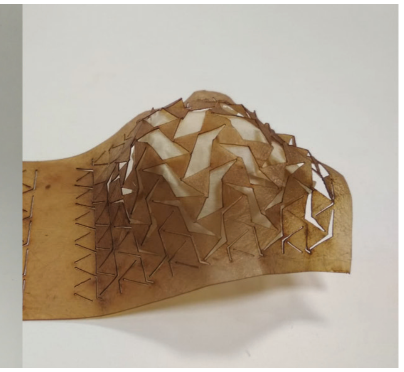
Microbial cellulose is a porous and highly hydrophilic material. This makes it barely resistant to water and humidity, but on the other side makes it behave like a sponge: it can absorb other fluids that can be embedded in the material and later released.
Its absorptive properties can be used also to dye the material after the harvest. The traditional dyeing techniques which use hot water baths are not the best way to colour the material, since water degrades it making it less flexible, more brittle and fragile. The best way to get coloured nanocellulose is during growth. If you want to dye it at a later time, you can soak it in an acidic dye as the culture medium, this will make the colour absorbed by the material without degrading it.

· dry > **surface treatment**

Porosity and hydrophily can be reduced through surface treatments, with the aim of making the material more durable because more resistant to environmental conditions as changes in humidity etc.
Many surface treatments have already been experimented with positive results such as beeswax or turpentine. However, as in the examples mentioned, they are often animal-based and therefore unethical or solvent-based and therefore harmful for the environment.
The best option appear to be vegetable oils such as tung oil, commercial name of an oil extracted from the tung tree – *Vernicia fordii* – which polymerises when exposed to hair, historycally used in ancient China to waterproof paper umbrellas or wooden boats.
When used to finish microbial cellulose, it gives the material a matte and smooth finish, preserving it from degradation.





· dry > **lasercut&engraving**

The material can be processed through laser cutting and engraving. Since it has a variable and not perfectly regular thickness, in order to get a better result each sheet of material needs to be tested individually to establish the proper parameters on the machine. Otherwise can happen to punch the material layer in correspondence of the thinner spots while engraving.
The laser cutter can be used for different purposes besides cutting out two-dimensional shapes out of the cellulose sheet, such as realising auxetic textures that can modify the material behaviour creating three-dimensional morphologies with a two-dimensional piece of material; engraving fold lines to facilitate the use of folding techniques such as Miura-Ori – technique invented by a Japanese astrophysicist consisting in the tesselation of a flat surface by parallelograms; or engraving text and symbols.


CA RB ON 28
BE ER 23
BE ER 23
CA RB ON 28


WI NE 06
WI NE 06


CA RB ON 28
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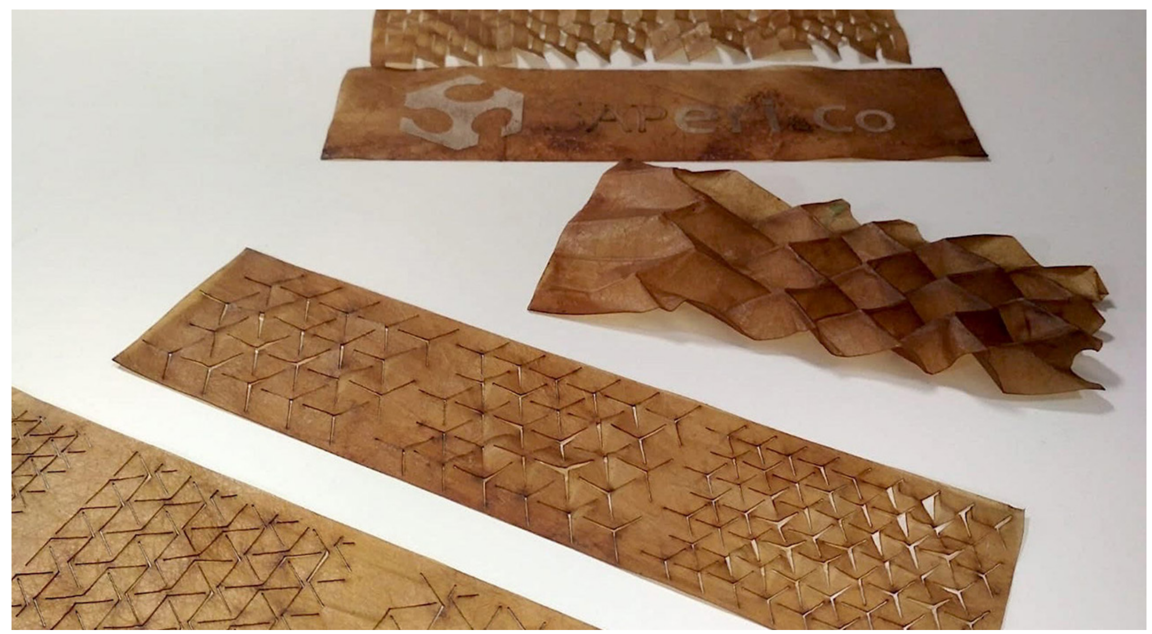
10


CA RB ON 28
BE ER 23
BE ER 23



· dry > **print**

The porosity of the material makes it suitable for printing, similarly to traditional paper.
Inks commonly found on the market, even the water-based ones, are synthetic and contain substances damaging to the environment. Natural inks are a niche product produced mainly by small artisans, not so easy to find. One of the reasons why natural inks are not so common is their short-lasting compared to synthetic ones, echo of the idea of permanence, eternity and immutability which characterised the industrial culture of the last centuries. This characteristic however, is useless when working with biodegradable materials which will fade over time together with the ink, making ephemeral compostable inks the best suited for printing purposes.

6.2.3. Contamination and Ageing

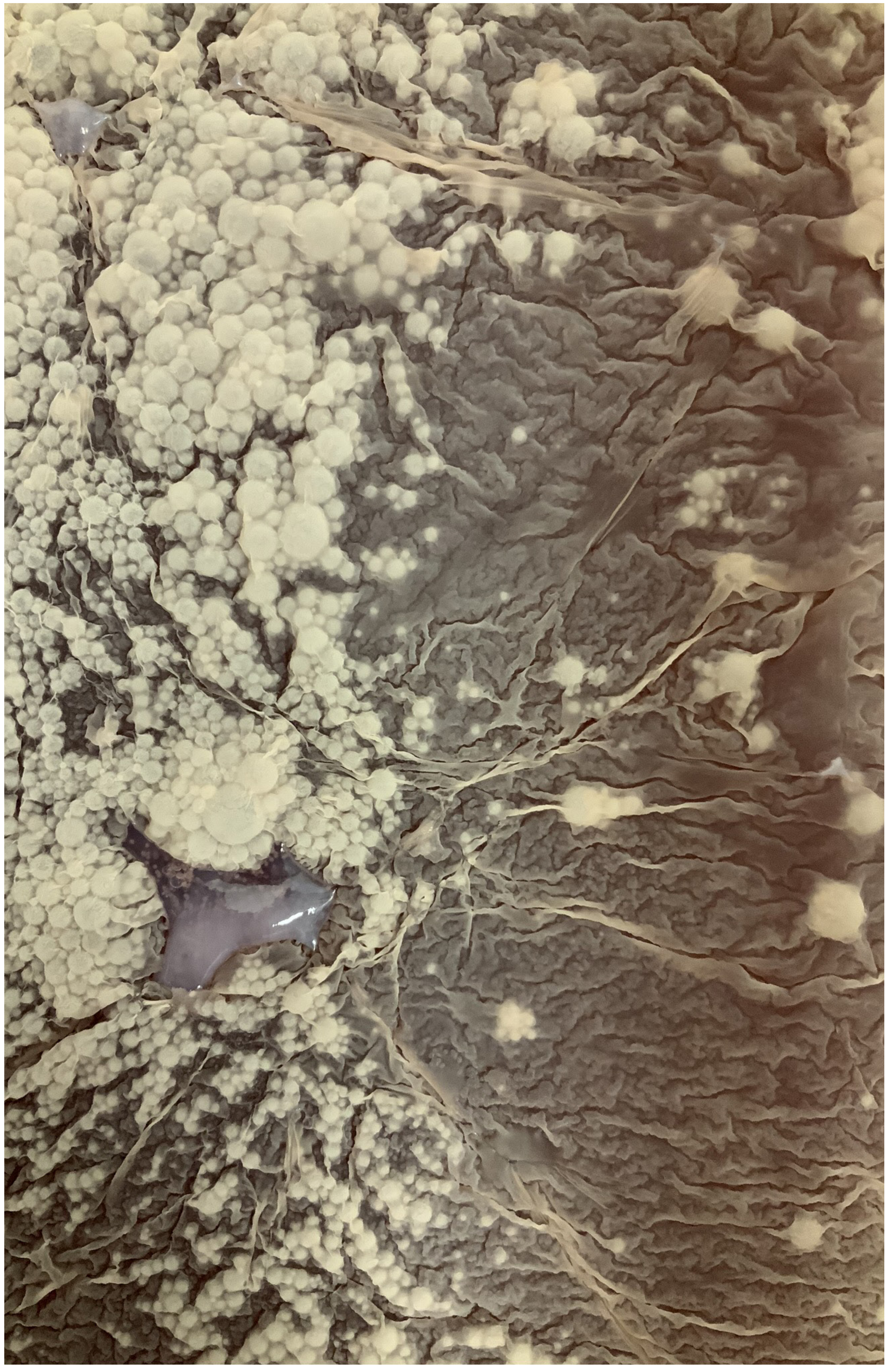
In the previous chapters we have seen how any living system is an open system affected by its environment. This makes it extremely prone to external contamination, especially if working in a not-sterile environment.

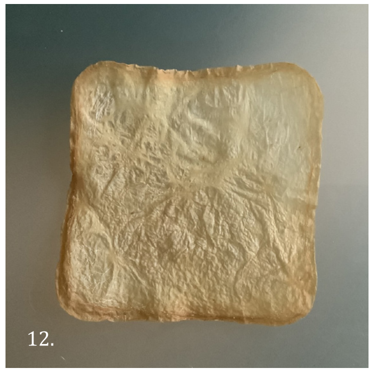
Contamination can occur from many sources, as using tools not thoroughly sterilised or handling ingredients with bare hands – we are estimated to have around 1500 bacteria living on each square centimetre of skin on our hands. But also simply from the surrounding air, which can carry microbial life too, wine for instance is particularly subject to this kind of contamination and not working under a fume hood makes it difficult to prevent contamination, unless working with small containers thus reducing the surface area in contact with air.

The smallest interaction can bring unexpected consequences not only in terms of contamination, for example even just moving the culture container during the growth process can affect the material stratification and therefore the final result.

As living material the interaction with microbial cellulose continues to be a dynamic one even after its fabrication. It is indeed responsive to environmental variations of temperature and humidity, and has a lifecycle which comprises ageing stages until reaching decay.

Microbial cellulose is a compostable material in balance with nature's decay and recovery processes, and this is why we have to use only pure biocompatible ingredients (inks, glues, surface treatments, additives etc) for its processing. It is characterised by an ephemeral nature which, rather than trying to counteract it, we need to accept and embrace as fundamental feature of life in our planetary ecosystem.

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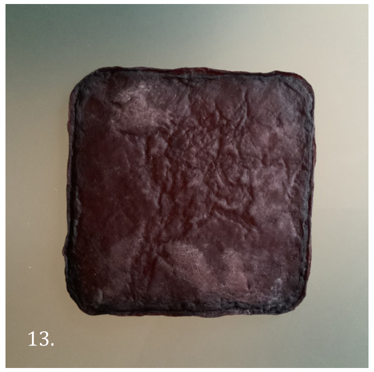
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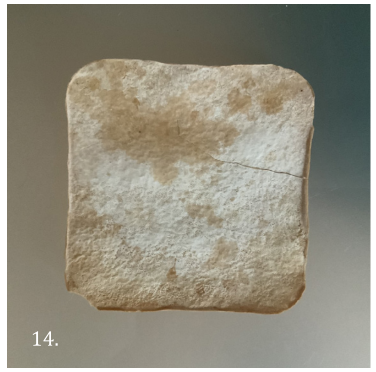
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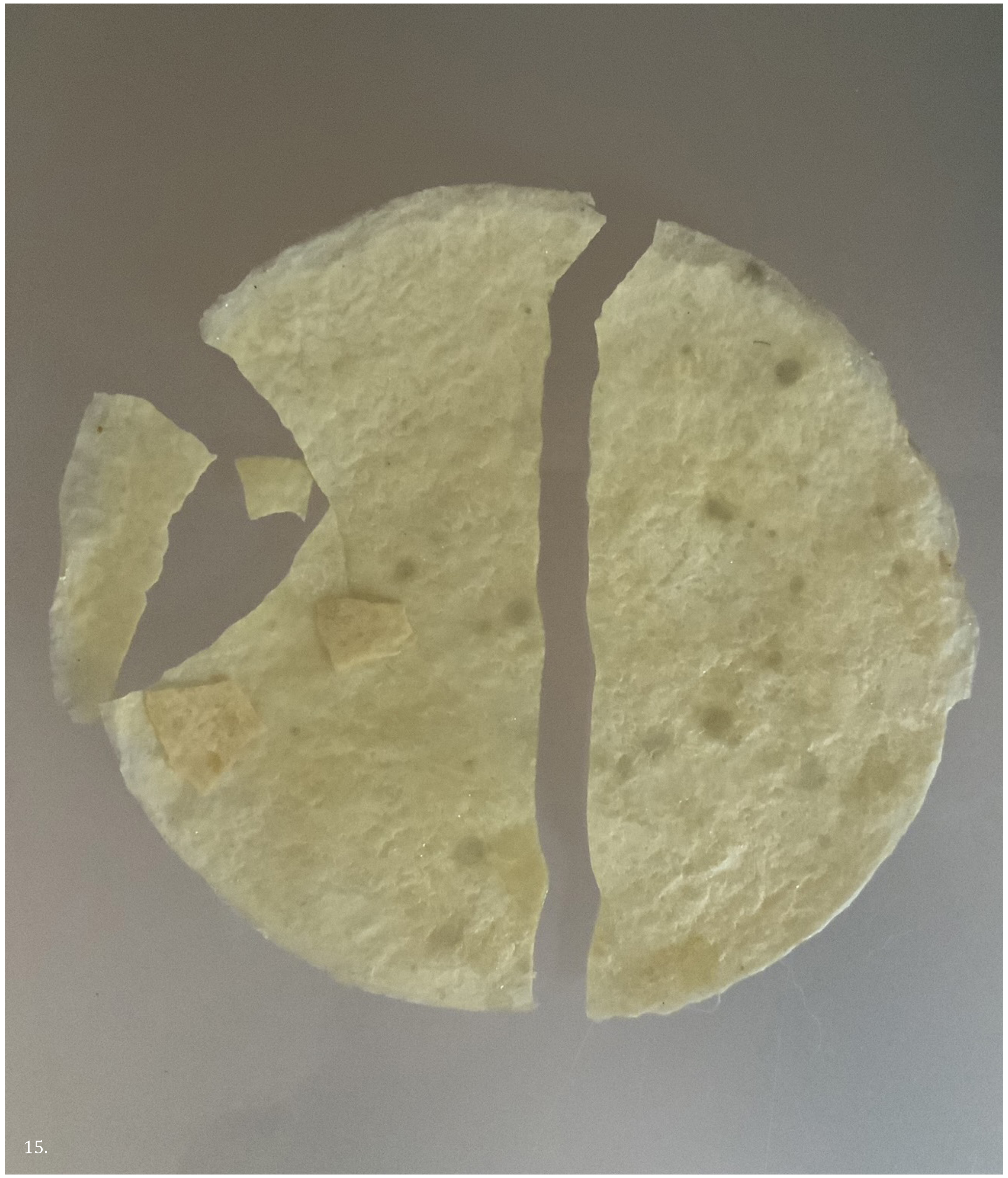
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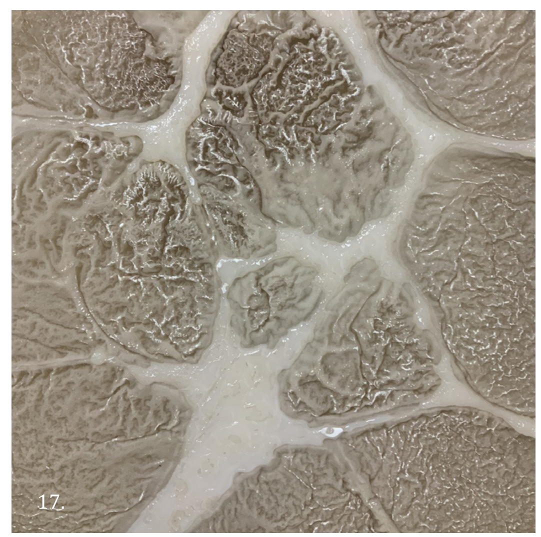
16.


17.

Aaging & Decay

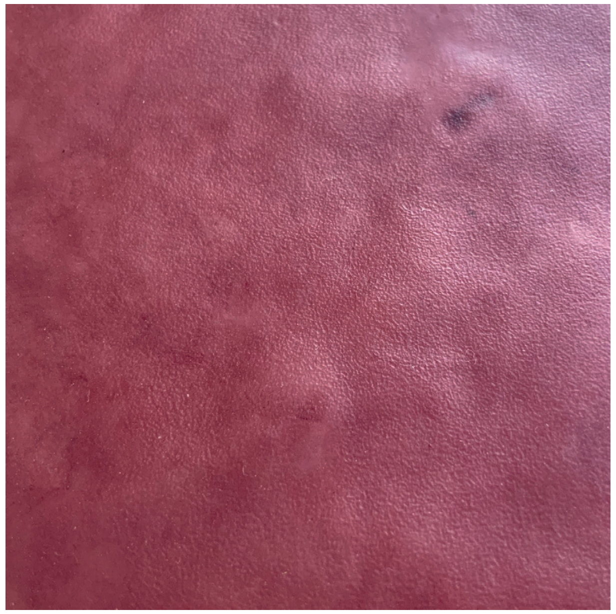
While aging the material gradually changes its co-lour, as whith oxidation processes, acquiring darker and brownish hues (img 16).
When subjectet to particularly “unconfortable” environmntal conditions as an extreme increase in the humidity rate microbial cellulose rapidly decays, losing its flexibility and becoming extremely brittle, and sometimes developing mould (img 12-15).

Contamination

When the culture undergoes contamination and mould formation can happen that cellulose and mould struggle for survival taking up space one to another (img 17).

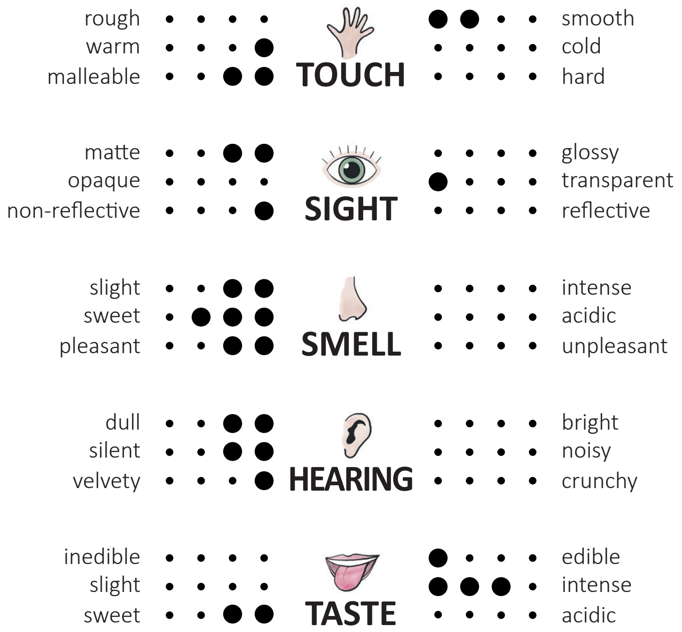
6.2.4. Material Archive

The material samples selected can acquire different perceptual features although starting from the same "recipe", depending on the drying phase which determines the surface finish, but also depending on external factors which can affect the fermentation process giving rise to a variety of textures.
A material produced with blueberry dye at a specific concentration for instance, can range from glossy to matte and to smooth to rough. It will have then a different set of characteristics according to the different techniques and tools used in each step of the production process. Just like on a craft product we can read the marks left from utensils, techniques and manipulation, in the same way on the biofabricated material we can read the marks left from the micro-artisans responsible for its production.
This material archive wasn't born with the objective of classifying nor listing specific protocols, but is aimed at illustrating in its breadth the spectrum of possibilities for microbial cellulose in terms of sensoriality, therefore contributing to define its identity – still a bit vague and blurry – through material experience and its stratification over time.



#F_01

blueberry dye 40%
polypropylene drying / natural finish



#F_02

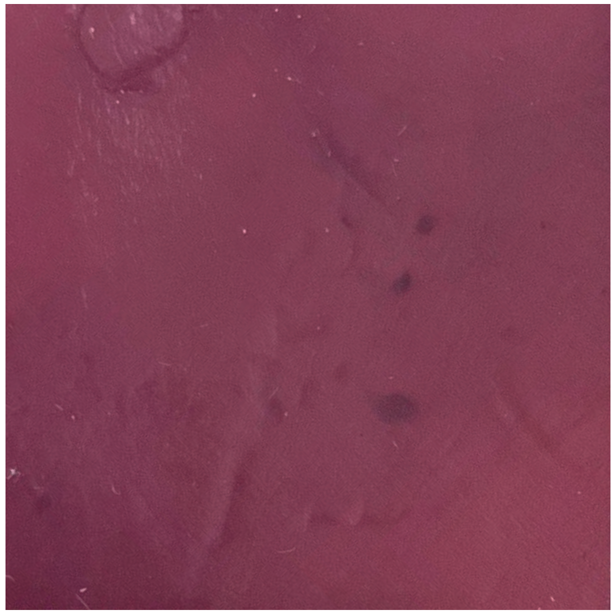
blueberry dye 20%
acrylic drying / tung oil finish

rough	• • • •	TOUCH	● ● ● ●	smooth
warm	• • • ●		● • • •	cold
malleable	• ● ● ●		• • • •	hard
matte	• ● ● ●	SIGHT	• • • •	glossy
opaque	• • • •		● ● ● •	transparent
non-reflective	• • • •		● • • •	reflective
slight	• • • •	SMELL	● ● ● •	intense
sweet	• • • •		● • • •	acidic
pleasant	• • • •		● • • •	unpleasant
dull	● ● ● ●	HEARING	• • • •	bright
silent	• ● ● ●		• • • •	noisy
velvety	● ● ● ●		• • • •	crunchy
inedible	• ● ● ●	TASTE	• • • •	edible
slight	• • • •		● ● • •	intense
sweet	• • • •		● • • •	acidic

#F_03

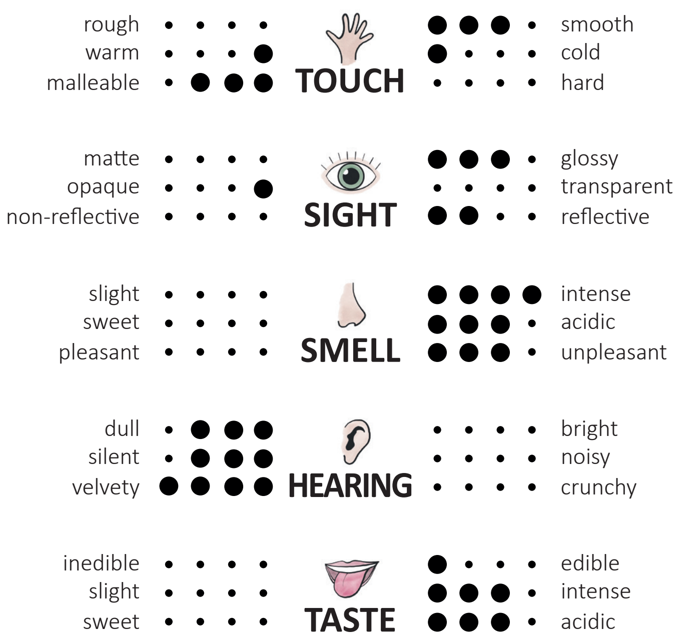
blueberry dye 10%
acrylic drying / natural finish

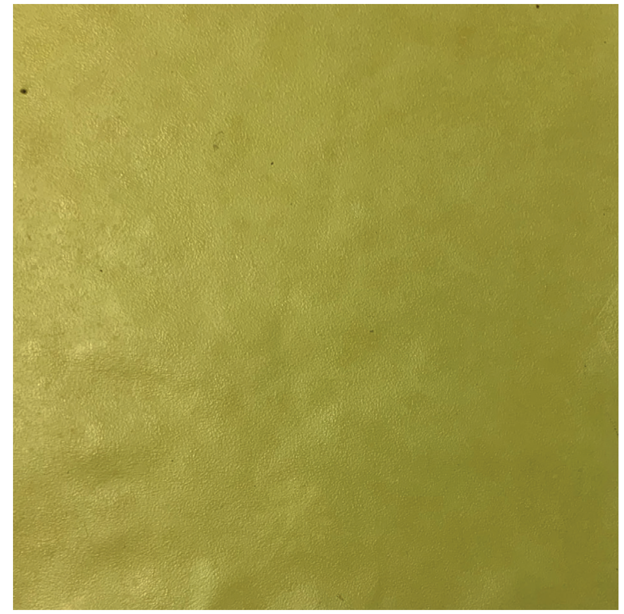
rough	• • • •	TOUCH	● ● ● ●	smooth
warm	• • • ●		● • • •	cold
malleable	● ● ● ●		• • • •	hard
matte	• • • •	SIGHT	● ● ● •	glossy
opaque	• • • •		● ● ● •	transparent
non-reflective	• • • •		● ● ● •	reflective
slight	• • • •	SMELL	● • • •	intense
sweet	• • ● ●		• • • •	acidic
pleasant	• • ● ●		• • • •	unpleasant
dull	● ● ● ●	HEARING	• • • •	bright
silent	• ● ● ●		• • • •	noisy
velvety	● ● ● ●		• • • •	crunchy
inedible	• • • •	TASTE	● • • •	edible
slight	• • • •		● • • •	intense
sweet	• • ● ●		• • • •	acidic



#F_04

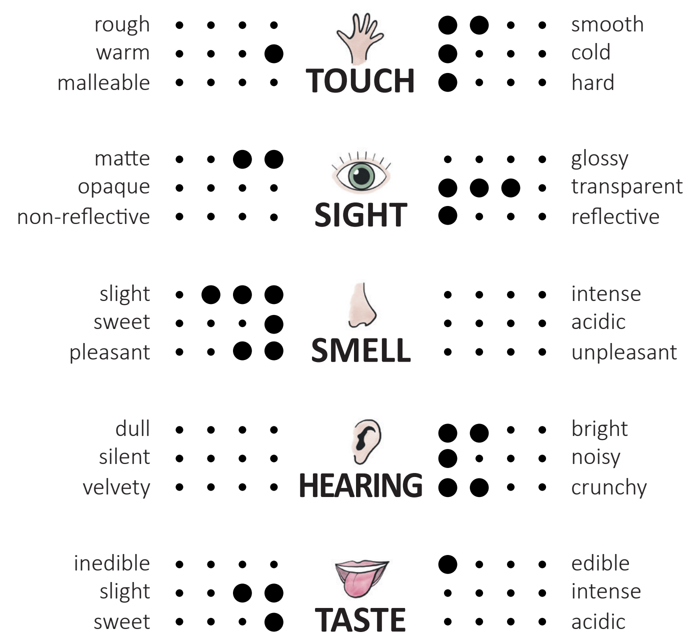
red wine
acrylic drying / natural finish

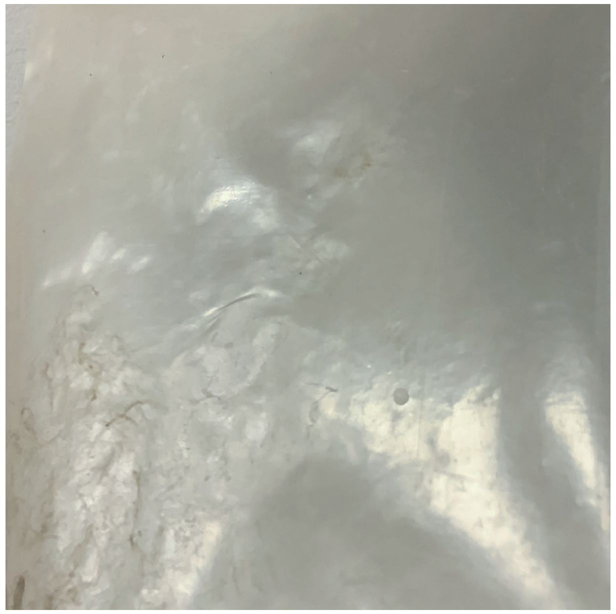




#F_05

turmeric
polypropylene drying / natural finish





#F_06

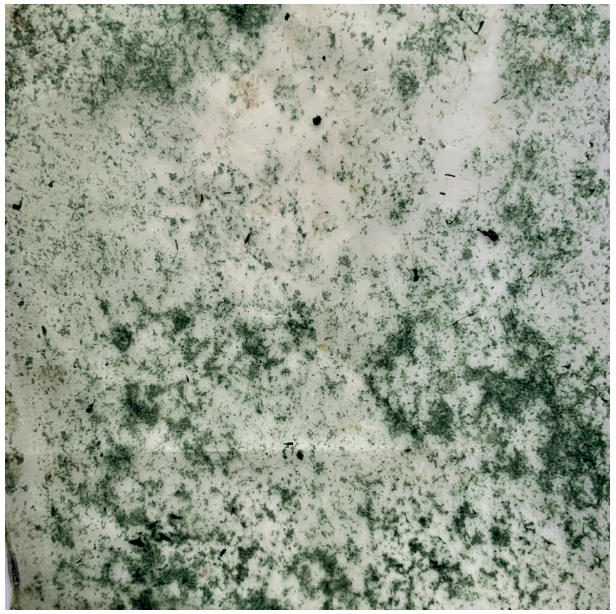
water
acrylic drying / natural finish

rough	· · · ·	TOUCH	● ● ● ●	smooth
warm	· · · ●		● · · ·	cold
malleable	· ● ● ●		· · · ·	hard
matte	· · · ·	SIGHT	● ● ● ●	glossy
opaque	· · · ·		● ● ● ●	transparent
non-reflective	· · · ·		● ● ● ●	reflective
slight	· ● ● ●	SMELL	· · · ·	intense
sweet	· · · ●		· · · ·	acidic
pleasant	· · ● ●		· · · ·	unpleasant
dull	· · ● ●	HEARING	· · · ·	bright
silent	· · ● ●		· · · ·	noisy
velvety	· ● ● ●		· · · ·	crunchy
inedible	· · · ·	TASTE	● · · ·	edible
slight	· · · ●		· · · ·	intense
sweet	· · · ·		● · · ·	acidic

#F_07

rice milk
acrylic drying / tung oil finish

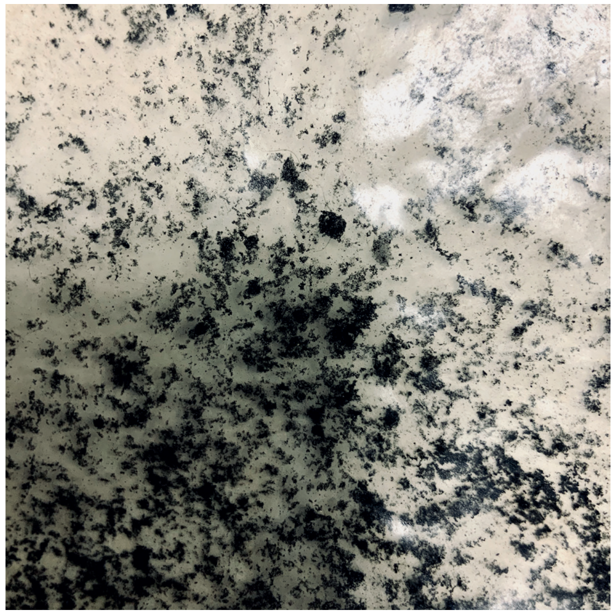
rough	· · · ·	TOUCH	● ● ● ●	smooth
warm	· · · ·		● ● · ·	cold
malleable	· · ● ●		· · · ·	hard
matte	· ● ● ●	SIGHT	· · · ·	glossy
opaque	· · · ·		● ● · ·	transparent
non-reflective	· · ● ●		· · · ·	reflective
slight	· · · ·	SMELL	● ● · ·	intense
sweet	· · · ·		● · · ·	acidic
pleasant	· · · ·		● · · ·	unpleasant
dull	● ● ● ●	HEARING	· · · ·	bright
silent	· ● ● ●		· · · ·	noisy
velvety	· · ● ●		· · · ·	crunchy
inedible	· ● ● ●	TASTE	· · · ·	edible
slight	· · · ·		● ● · ·	intense
sweet	· · · ·		● · · ·	acidic



#F_08

spirulina powder
natural drying / natural finish

rough	• • ● ●	**TOUCH**	• • • •	smooth
warm	• • ● ●		• • • •	cold
malleable	● ● ● ●		• • • •	hard
matte	• ● ● ●	**SIGHT**	• • • •	glossy
opaque	• • • •		● ● • •	transparent
non-reflective	• ● ● ●		• • •	reflective
slight	• • • •	**SMELL**	● ● • •	intense
sweet	• • • ●		● • • •	acidic
pleasant	• • • •		● • • •	unpleasant
dull	• • ● ●	**HEARING**	• • • •	bright
silent	• ● ● ●		• • • •	noisy
velvety	• ● ● ●		• • • •	crunchy
inedible	• • • •	**TASTE**	● • • •	edible
slight	• • • •		● • • •	intense
sweet	• • • •		● • • •	acidic



#F_09

charcoal powder
acrylic drying / natural finish

rough	• • ● ●	**TOUCH**	• • • •	smooth
warm	• • • ●		• • • •	cold
malleable	• • ● ●		• • • •	hard
matte	• • • •	**SIGHT**	● ● ● •	glossy
opaque	• • • •		● ● • •	transparent
non-reflective	• • • •		● ● ● ●	reflective
slight	• ● ● ●	**SMELL**	• • • •	intense
sweet	• • • ●		● • • •	acidic
pleasant	• • • ●		● • • •	unpleasant
dull	• • • •	**HEARING**	● • • •	bright
silent	• • • •		● • • •	noisy
velvety	• • • •		● ● • •	crunchy
inedible	• • • •	**TASTE**	● • • •	edible
slight	• • • ●		● • • •	intense
sweet	• • • ●		● • • •	acidic

#C_01

charcoal 3% | fine-grained
wet scoby pulp

rough	• ● ● ●	TOUCH	• • • •	smooth
warm	• • • ●		• • • •	cold
malleable	• • • ●		• • • •	hard
matte	● ● ● ●	SIGHT	• • • •	glossy
opaque	● ● ● ●		• • • •	transparent
non-reflective	● ● ● ●		• • • •	reflective
slight	● ● ● ●	SMELL	• • • •	intense
sweet	• • • ●		● • • •	acidic
pleasant	• • • ●		● • • •	unpleasant
dull	• ● ● ●	HEARING	• • • •	bright
silent	• • ● ●		• • • •	noisy
velvety	• • • ●		• • • •	crunchy
inedible	• • • •	TASTE	● • • •	edible
slight	• • • •		● • • •	intense
sweet	• • • •		● • • •	acidic

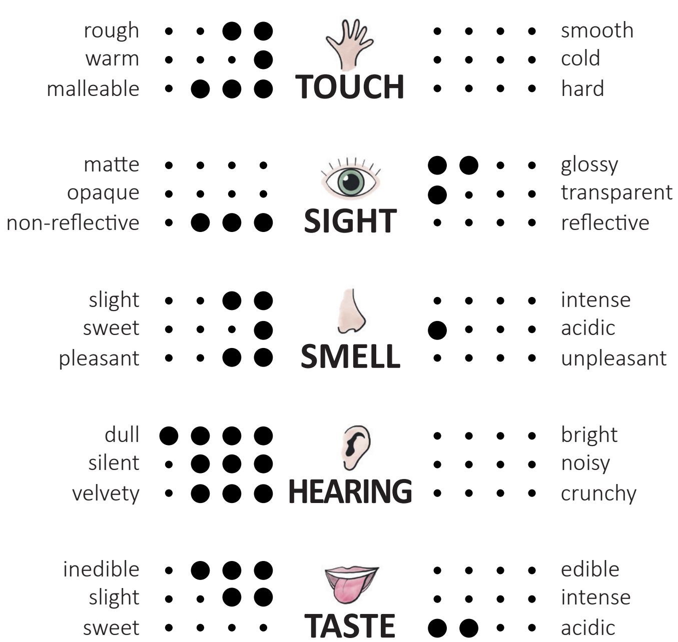
#C_02

charcoal 7% | medium-grained
wet scoby pulp

rough	● ● ● ●	TOUCH	• • • •	smooth
warm	• • ● ●		• • • •	cold
malleable	• • • •		● ● ● •	hard
matte	● ● ● ●	SIGHT	• • • •	glossy
opaque	● ● ● ●		• • • •	transparent
non-reflective	● ● ● ●		• • • •	reflective
slight	● ● ● ●	SMELL	• • • •	intense
sweet	• • • ●		● • • •	acidic
pleasant	• • • ●		● • • •	unpleasant
dull	• ● ● ●	HEARING	• • • •	bright
silent	• • • ●		• • • •	noisy
velvety	• • • •		● ● • •	crunchy
inedible	• • • •	TASTE	● • • •	edible
slight	• • • •		● • • •	intense
sweet	• • • •		● • • •	acidic

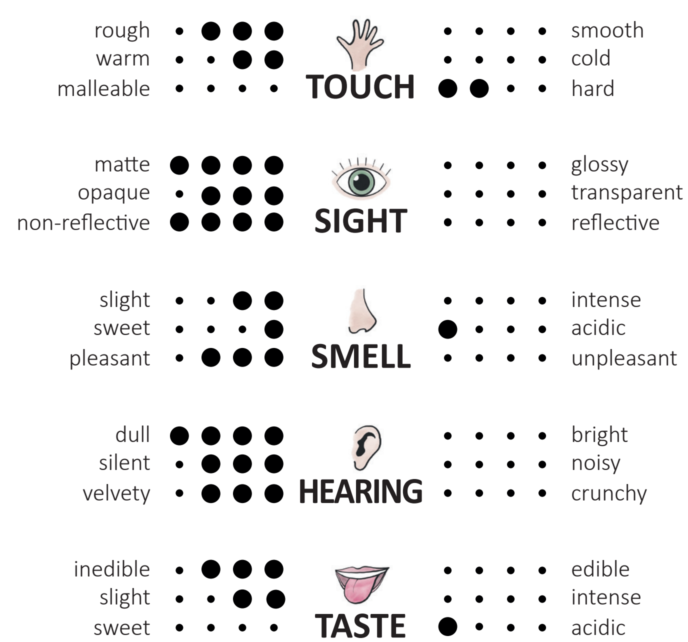
#C_03

coffee grounds 25%
wet scoby pulp



#C_04

coffee grounds 35%
wet scoby pulp

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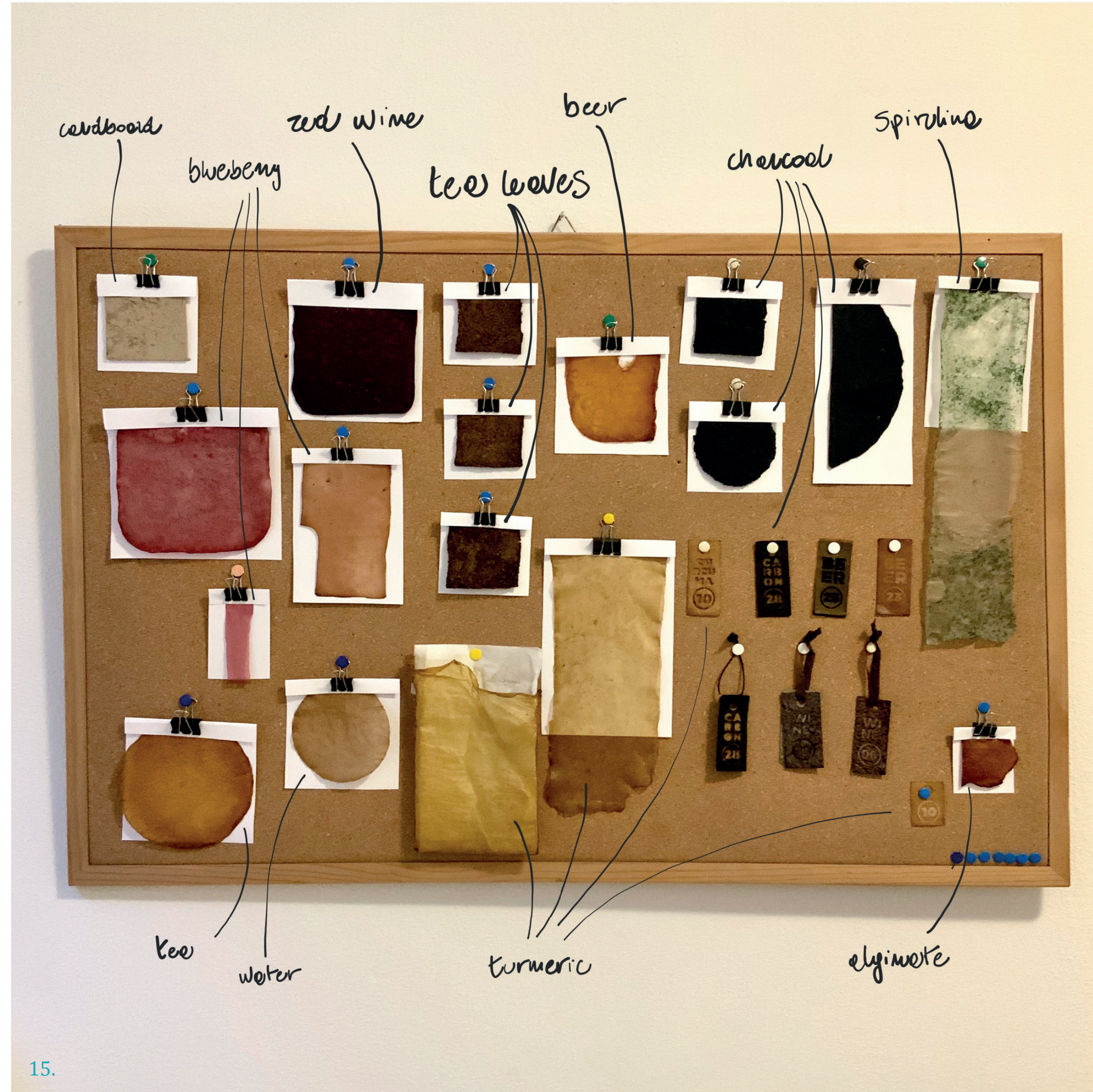
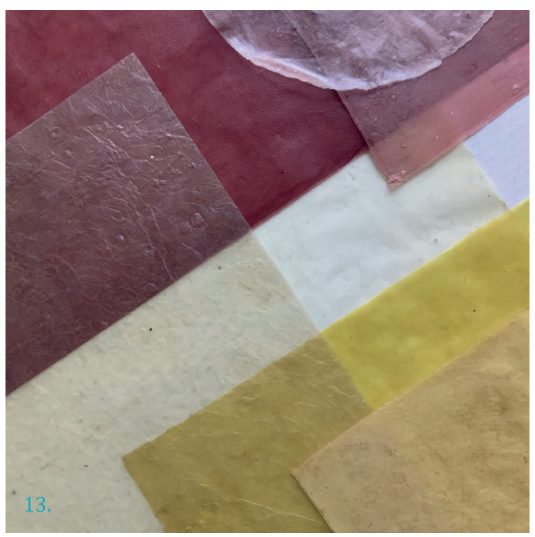


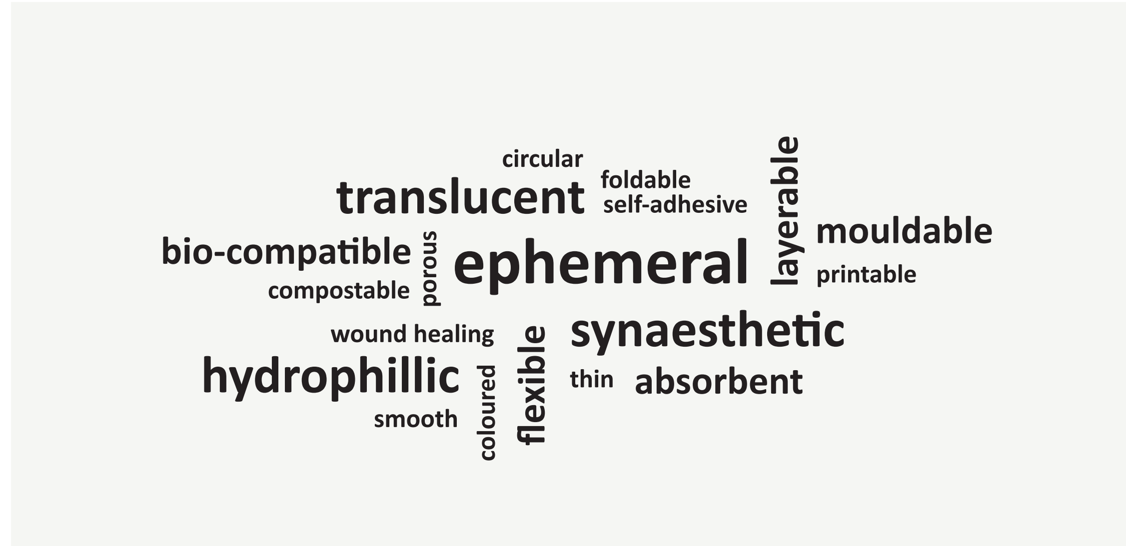
15.


13.

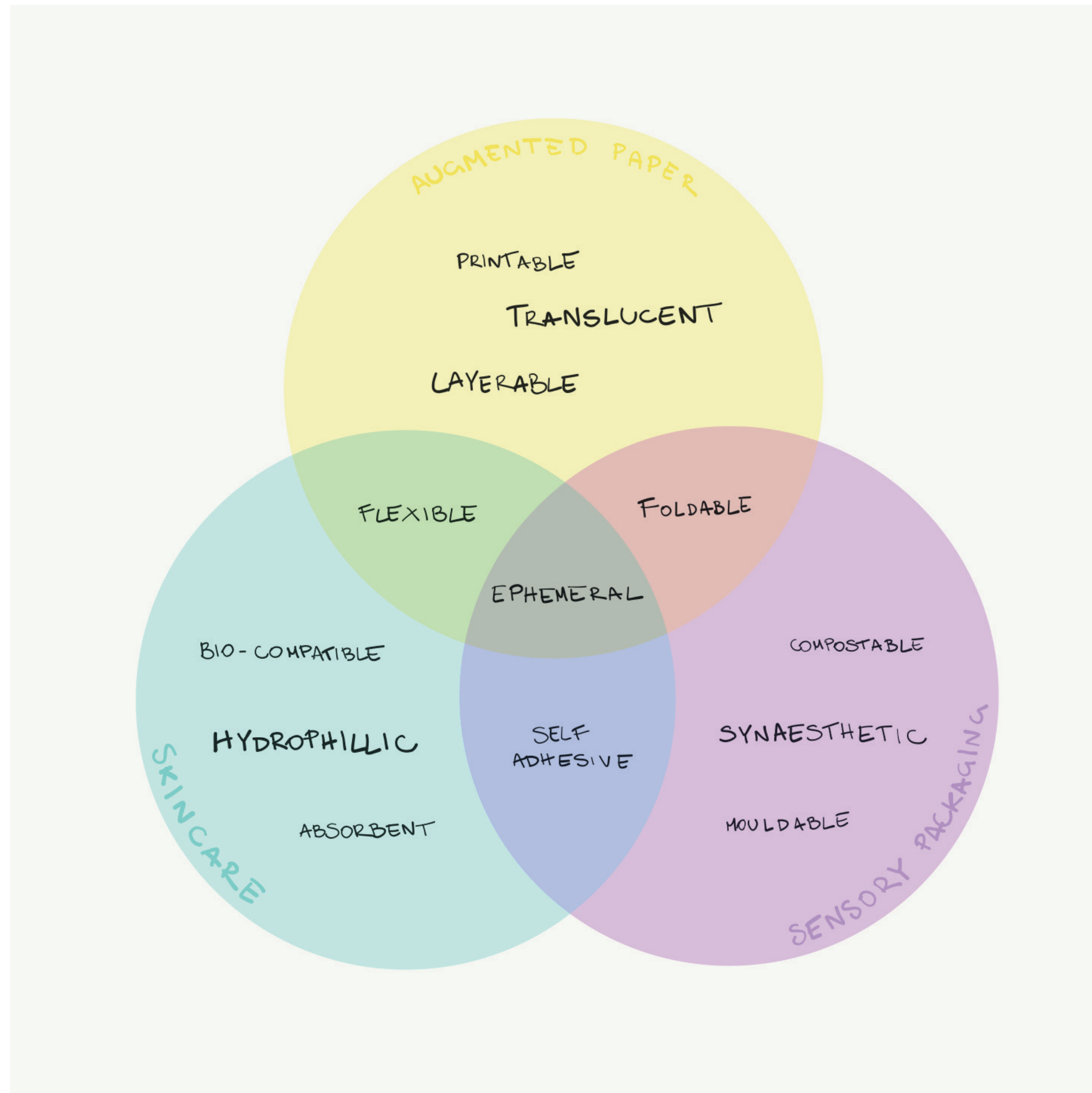

14.


16.

12-14. Microbial Nanocellulose sensory exploration: various samples
15. Microbial Nanocellulose Material Archive
16. Microbial Nanocellulose Aged Material Archive: the samples collected have different ages, from the oldest ones realised a year and a half ago to the newest, realised about six months ago. All the samples have been exposed to unfavourable weather contitions as direct sunlight, temperature changes and huge humidity, in order to observe their behaiour and duration when stressed and pushed to the limit.



6.3. Application Scenario



Starting from material's features, analysed through tinkering and manipulation, as well as through stressing the material to investigate its potential and limitations, feasible application scenarios have been identified.
The scenarios have been chosen and developed based upon the ability to turn such features and peculiarities into the product added value. Microbial cellulose is an ephemeral material with a short or medium life-span, able to easily biodegrade returning nutrients to the environmental system. It is therefore pointless to try to force the material into durable applications in the attempt to control and subdue it, going against its own character. Trying to engineer it to make it waterproof, or mixing it to other bio-polymers in order to radically change its behaviour – thus using it as a mere filler –, is indeed a way to distort its identity and character.
On the contrary, the approach followed within this research places the material as creative input of the project (Lucibello, 2018), basic element with well defined features which will guide us within the design process. According to the features emerging from the previous stages of material experimentation, three main macro-scenarios have been identified:

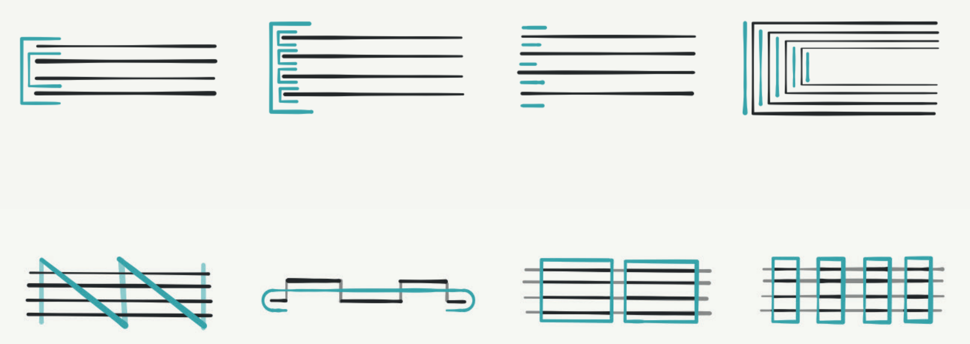
- *augmented paper*, since microbial cellulose has characteristics common to traditional paper (vegetable cellulose) plus extra features such as translucency and flexibility;
- *sensory packaging* with synesthetic features, self-adhesive and self-produced from organic waste;
- *skincare*, for its biocompatibility, absorption and wound-healing properties.

All of the scenarios involve the implementation of the material into products that are relatively short-lived, ranging from single-use disposable products to medium-term applications, in accordance with the material durability.

6.3.1. Augmented Paper

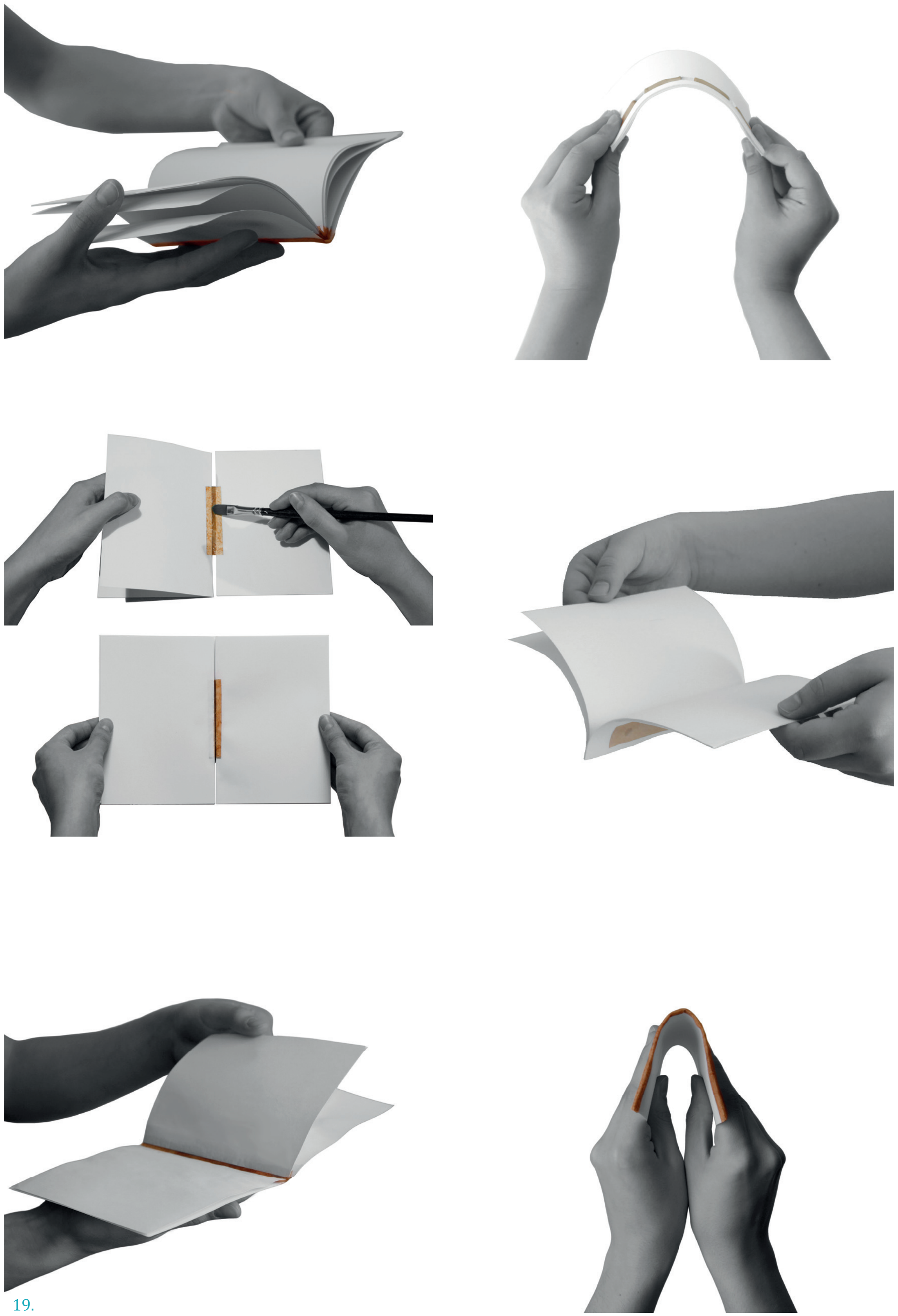
17-18. Typologies of bookbinding techniques experimented by M. Campanella, L. Laricchiuta and C. Summa for their thesis work, supervised by Prof. R. Carullo from Bari Polytechnic University

Microbial cellulose shows some common features with vegetable cellulose, as for instance the possibility to be printed just as traditional paper. It has however also some distinctive features as translucency, flexibility and multisensoriality which make it an *augmented paper*.
Paper is part of our everyday life, a material with which we interact multiple times and in different ways throughout a regular day. It can indeed assume different characteristics according to diverse processing techniques, on the basis of which it is implemented in various applications. Some of them are more durable – books, certificates, photographies, love letters – but many of them are ephemeral or even single-use: tickets, receipts, labels, notes, flyers, leaflets, advertising posters, envelopes, paper bags and so on.
Paper is often regarded as an environmental-friendly material, recyclable and able to disappear completely after a rainy day. Moreover it embodies the idea of craft making, and for this reason is often used in place of plastic shopping bags for luxury or tailor-made clothing. Such image however is pretty far from reality, since paper is a "fully fledged industrial product" with an high environmental impact (Miodownik, 2013). As mentioned in previous chapters indeed, paper recycling always requires a certain amount of virgin cellulose and is therefore a sub-cycling process which reduces the quality of the material produced over time. Furthermore, "the impact in terms of energy usage of a single-use paper bag has been found to be greater than that of a plastic bag" (Miodownik, 2013).
For the spectrum of paper ephemeral applications microbial cellulose represents a valuable circular alternative to vegetable cellulose, whose distinguishing features – including the short durability – can confer added value to the products. Microbial cellulose can therefore be implemented as *augmented paper:* flexible, soft and translucent it can be crumpled as a fabric without losing its smoothness. Unlike traditional paper it doesn't require powders, chemical bleaches and coatings (traditionally used for paper making in order to turn the brown raw material into a white smooth sheet), nor the delignification process used to extract it from wood and se-



17.

18.



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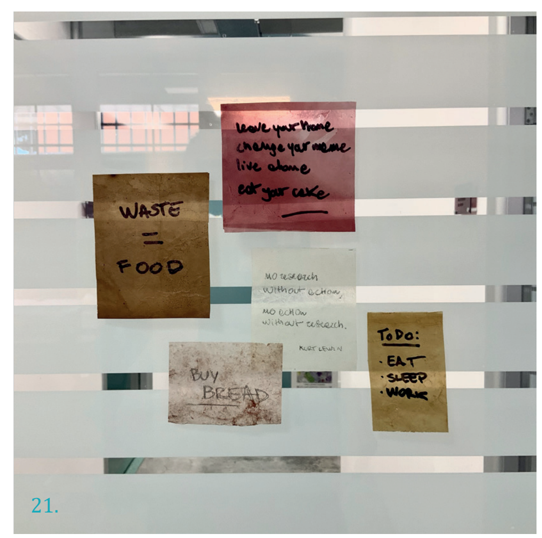

21.

19. Typologies of bookbinding techniques experimented by M. Campanella, L. Laricchiuta and C. Summa

20-21. Augmented paper scenario: sticky memo. Microbial cellulose sheets can be used as biodegradable note paper, by getting the material wet and exploiting the resulting self-adhesiveness to stick it on various surfaces with no need of glue. Once removed the notes can be collected and bound together parate it from lignin. As vegetable cellulose it can be printed, folded and stratified, moreover its translucency allows to obtain different effects and gradations of transparency-opacity.

The author collaborated with Prof. R. Carullo from Polytechnic University of Bari and her students M. Campanella, L. Laricchiuta and C. Summa, in order to explore the augmented paper scenario. The thesis work investigated differences and similarities between vegetable and microbial cellulose, and how the two materials interact one another.
The aim was to understand how microbial cellulose behaves when in contact with vegetable cellulose, in terms of adhesion/detachment, stiffness/flexibility, opacity/transparency. As a result, because of the adhesive properties of microbial cellulose which emerged from the experimentation, several book binding techniques have been tested and implemented. All the binding systems experimented were developed around the combination between flexibility and self-adhesive properties of microbial cellulose and the stiffness of vegetable one. The binding were realised using microbial cellulose as supporting structure for the booklets, and the stiffness/solidity ratio resulting from the combination of the two materials proved to be a structural element besides an aesthetic one.
The first tests were focused on existing binding techniques, and were useful to provide an understanding of the material properties and behaviour. Subsequently, innovative ways to combine the two materials were explored, which lead to the development of a system through which joining loose sheets and note papers with microbial cellulose stripes, which allows to add a sheet at any time just wetting the stripe.

In the course of the research, experiments and tests have been made using microbial cellulose sheets for letterpress printing. This part of the experimentation took place at Slab letterpress in Rome[2]. The tests were made using the technique of movable type printing, with a printing press and lead types. Graphic elements were printed together with textual ones using an acrylic stereotype made with rapid manufacturing technology at SAPeri&co's fab lab, which was juxtaposed to the historical lead types.
The material used were both untreated and coated with tung oil. The prints were successful in both cases except for the material samples where the tung oil coating was very thick preventing the ink absorption, in this case the ink took several weeks to dry completely. Particularly uneven sheets with a variable thickness will de-

2. Slab Letterpress has been found in 2018 by Elettra Scotucci and Andrea Vendetti in Rome, IT, with the aim of saving, preserving and valorising the tangible and intangible heritage of typography and letterpress printing.
Their activity, besides printing services and educational workshops, involves the recovery of printing machinery and historical typeface sets, which are restored and archived in order to preserve their historical memory and allow their use, experimenting the application of ancient typefaces for contemporary visual communication.


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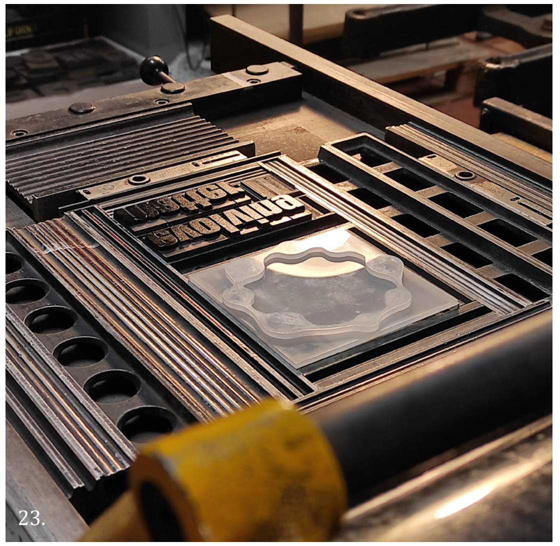
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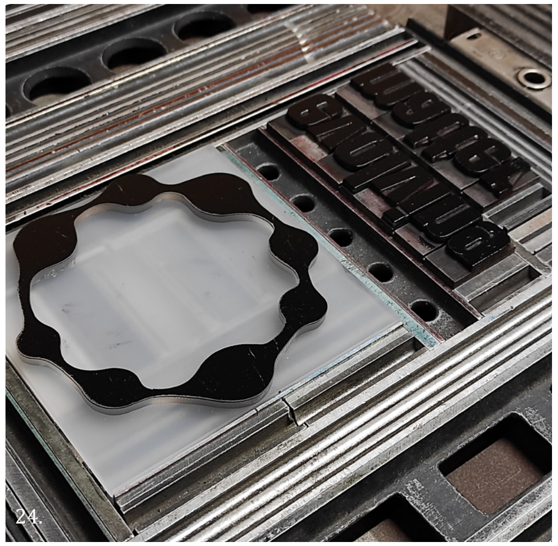
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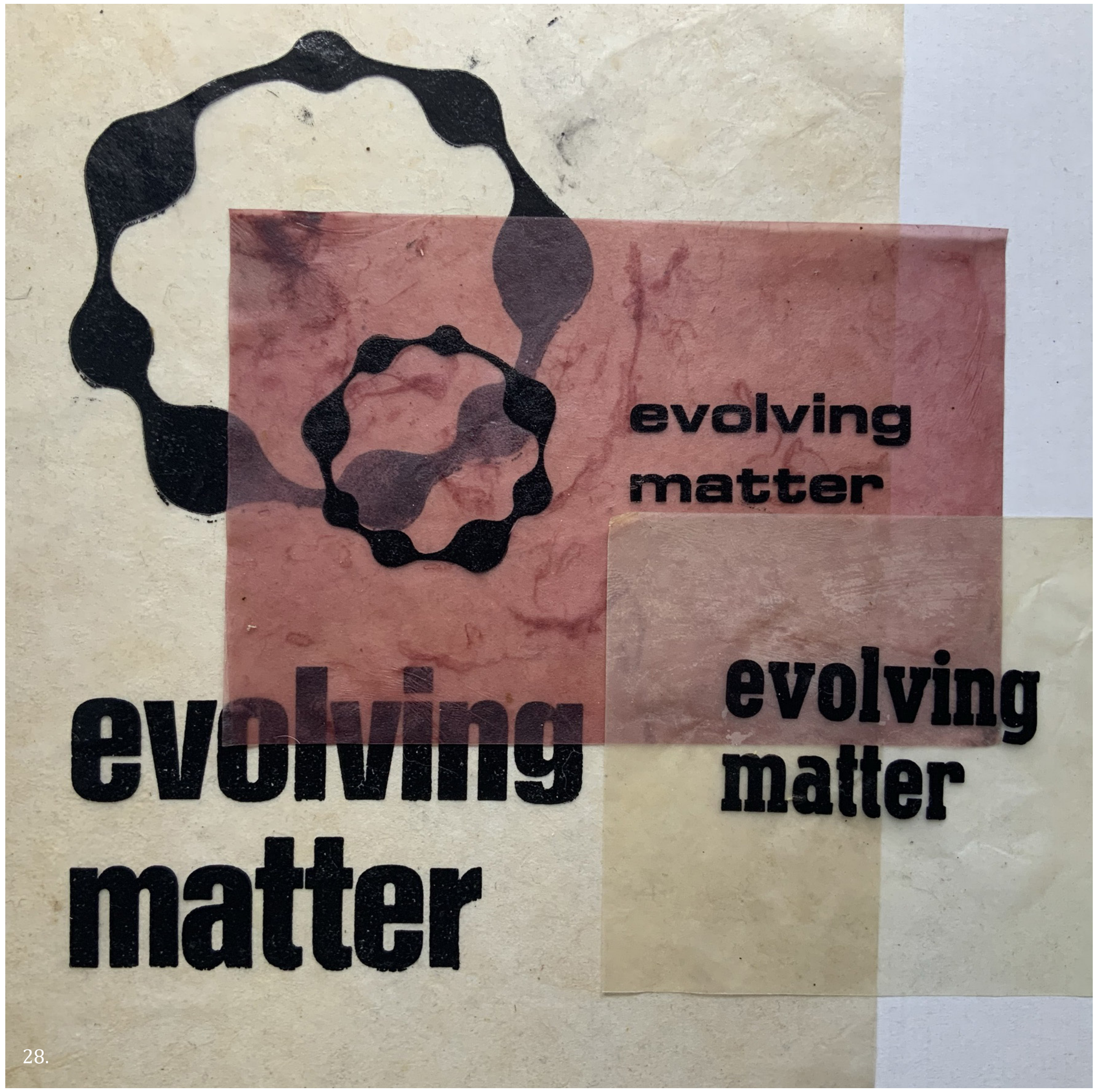
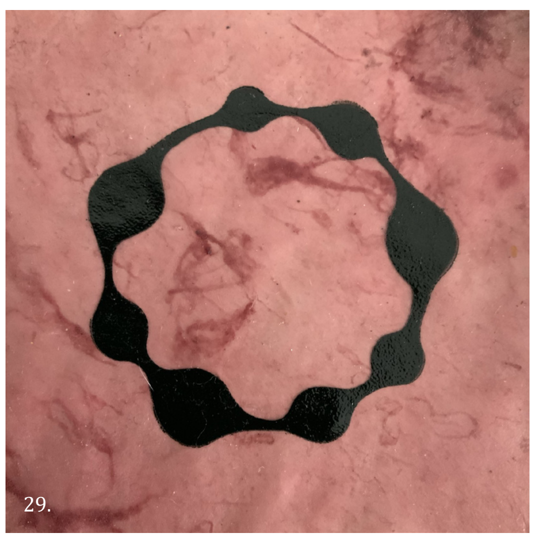
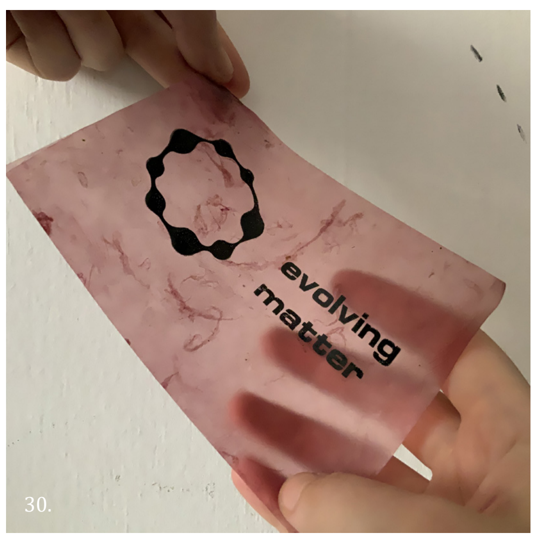
22-27. Printing tests @ Slab letterpress, Rome



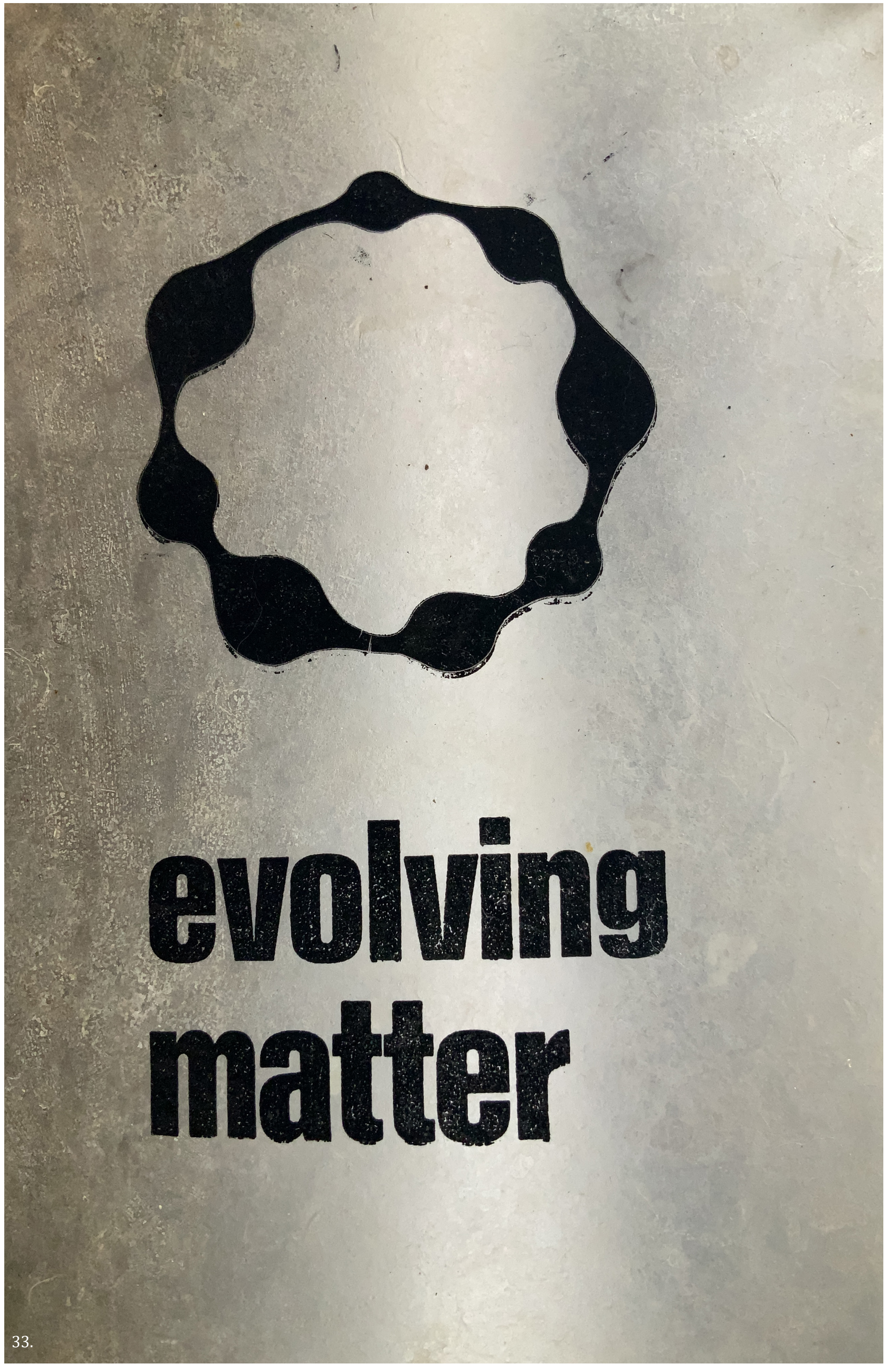




28. Microbial Nanocellulose printing tests: water-based and blueberry-based materials - realised @ Slab Letterpress
29-30. Microbial Nanocellulose printing tests: blue-berry-based sample - realised @ Slab Letterpress
31. Microbial Nanocellulose printing tests: mixed materials - realised @ Slab Letterpress
32. Microbial Nanocellulose printing tests: tea-based, coffee-based and water-based samples. Materials with different surface textures and finishes result in different modes of ink deposition, absorption and drying

33. Printing test on water-based microbial cellulose treated with tung oil - realised @ Slab letterpress
34. Printing tests @ Slab letterpress, mixed materials

termine a not-uniform imprint of the ink, as opposed to the more regular ones; very thin sheets instead, may break along the edges of the types because of the pressure exerted. The flexibility of microbial nanocellulose revealed to be a problem for letterpress printing, making the placement of the sheet upon the press a bit challenging, especially for larger ones. Other printing techniques as silk-screen printing for instance, where the sheet is positioned under the printing matrix and not over it, could be more appropriate in this regard.



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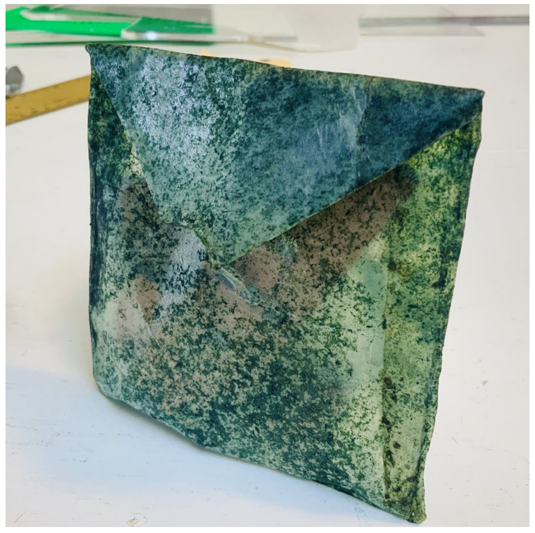
6.3.2. Sensory Packaging

The ephemeral nature of microbial nanocellulose makes it a suitable material for several applications within the packaging field. Currently, the packaging industry represents one of the most emblematic examples of blind and unconscious material application. It is indeed grounded on the implementation of extremely durable materials – mainly fossil-based polymers – for single-use products, ranking among the main causes of plastic pollution and environmental crisis.
The microbial fermentation process can be harnessed for the self-production of packaging elements – from labels to shopping bags – giving new life and value to production waste and byproducts.
As previously explained within the growing experiments, microbial nanocellulose can be fabricated using different kinds of food and beverage waste, which represent a still valuable food source for microbial fermentation. Food and beverage companies such as wine producers, beer or kombucha breweries, coffee shops, juice bars and so on, can therefore access raw matter available at no cost and use it to self-produce tailor-made packagings on the spot, furthermore eliminating transportation impact and costs.
The use of waste doesn't just brings benefits in terms of cost-effectiveness and eco-compatibility, it represents indeed also a vehicle for semantic and sensory features which confer the final artefact a strong perceptual characterisation (Lucibello et al, 2020). The resulting material will be equipped with a sensory plus, providing the user with a synaesthetic experience. The organoleptic properties of the product (e.g. craft beer or wine) as colour or smell are transferred to the material, which will thus communicate its identity through multiple sensory channels. In addition, the self-adhesive properties of microbial cellulose due to its sugar content, can be easily reactivated wetting the material with water, and exploited for the production of adhesive labels and stickers which won't require the use of any glue, preserving the compostability of the packaging elements.

Packaging

Nanocellulose sheets can be folded to create bags, cases etc. If still wet the material will self-seal while drying. Otherwise the dry material can be sealed through heath or re-wetting and folding the parts to be connected.



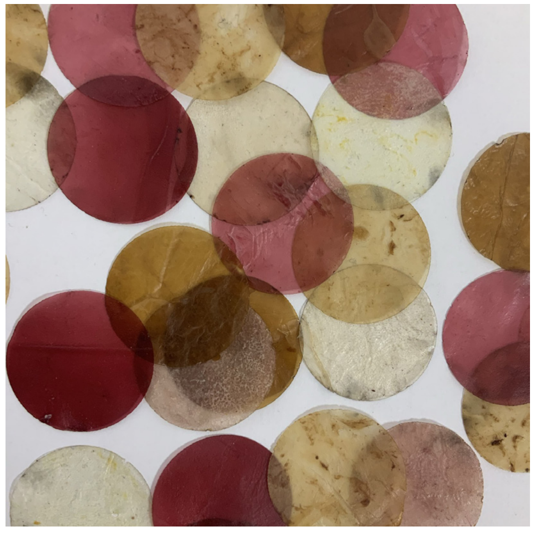
Labels

Self-adhesive properties of microbial cellulose makes it suitable for the realisation of adhesive labels. The material can be both printed or laser cutted, overlapping sheets of different colours to create a relief effect.

6.3.3. Healing Second Skin

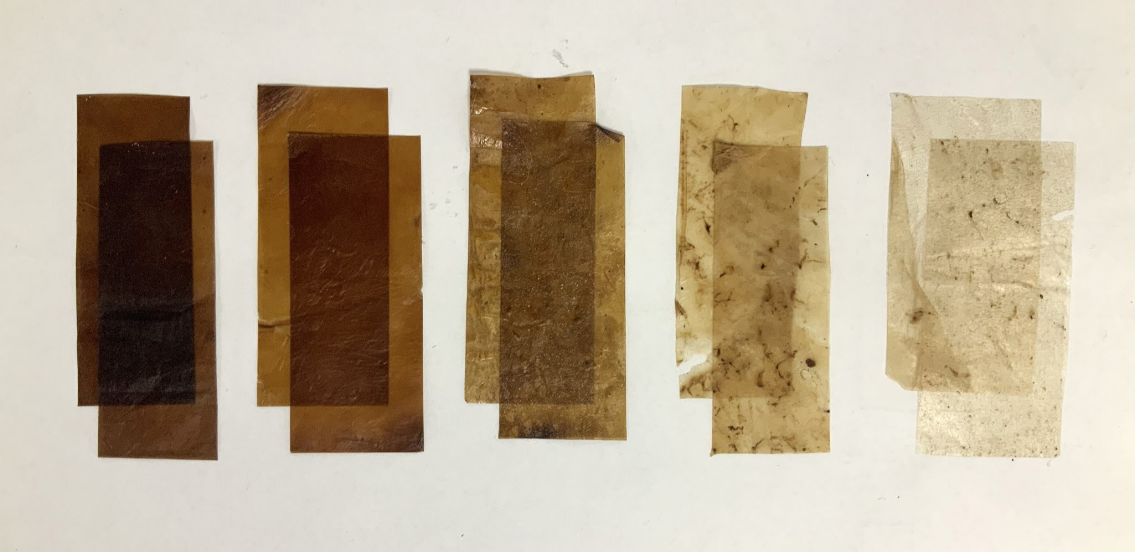
Hydrophilic properties of microbial nanocellulose, which make it unsuitable for certain applications (e.g. microbial "leather" as a substitute for animal leather in fashion design products), prove to be an added value when considering different application scenarios. Its great absorbency indeed, makes it behave like a sponge when in contact with fluids, providing the possibility to incorporate dermocosmetic treatments inside it.
Soaking the material into any kind of skincare treatment in liquid form, will get the treatment absorbed by the material, and later released on the skin. Microbial nanocellulose has indeed a very high water-holding capacity, being able to absorb up to a hundred times its dry mass (Bielecki et al., 2013). It is a totally biocompatible material which can be sterilised and safely used in contact with living tissues; moreover it already has in itself wound healing properties, which makes it perfect for the implementation in wound dressings and skincare products.
The material is already used for cosmetic applications, but mainly as an ingredient in moistening creams. Its nano size in fact, makes it able to penetrate through skin pores and act as drug carrier (Ioelovich 2008). Looking at its technical-performative characteristics, microbial cellulose proves to be able of releasing moisture while simultaneously absorbing exudates, acting as physical barrier which provides protection from external contamination and at the same time allows air transpiration (Bielecki et al., 2013).
Therefore, microbial cellulose is well suited to be used as second skin with healing properties. It can then be used to fabricate plasters and bandages of different sizes, requiring no glue nor surgical tabe because of its self-adhesive properties. It is transparent enough to monitor the state of the wound without removing the bandage, can be shaped according to the body morphology easily adapting to twists and turns, and can be painlessly removed and thrown in the compost bin after use.
Such properties makes it a valuable material also for tattoo aftercare treatments: it is able to protect the wounded skin, absorb

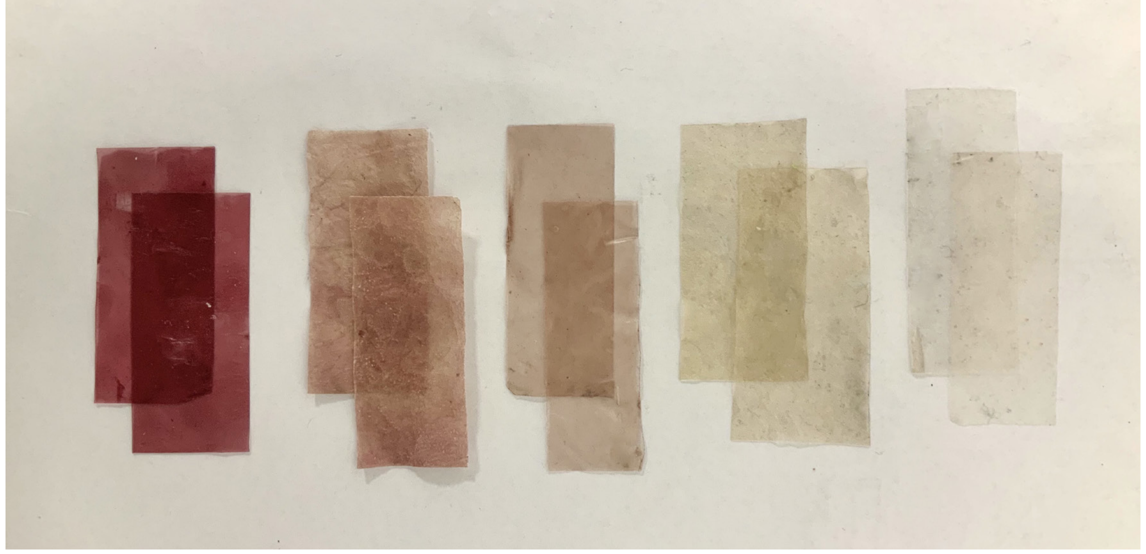
secretions, keep the area moist and release soothing substances which can be soaked into it. Moreover it can be customised to perfectly cover any tattoo shape and size, it can be made more or less transparent in order to show or hide the new tattoo, and it can be realised in skin shades for a natural look or designed with vibrant colours and textures, through which turning such medical device into a fashion accessory.
Besides wounds and burns treatment, microbial cellulose represent a precious material also for dermocosmetic applications. It can be used both in sheets or pulp and combined with curative substances through absorption or blending. According to the kind of additives and nutrients embedded it can be used for different skin areas and requirements, while its textile-like behaviour when dry opens up the possibility to produce solid cosmetics – face masks, scrub pads, acne treatments etc. – which won't require waterproof plastic packagings, nor textile scaffolds (as for traditional face masks), and which can be just washed away and biodegrade after the use.



Patches and Bendages

Nanocellulose bandages are self-adhesive. To use them simply wet them to re-activate the adhesiveness and place them on your skin. Since extremely flexible and malleable they will perfectly adapt to the different body morphologies.
They can be produced in various shapes and sizes to suit various needs: stripes, circles but also sheets or ribbons to be cut to size for tailored dressings. Furthermore they can be produced in natural shades to match skin tones, in bright and warm colours, and even transparent.





6.4. Diffuse micro-factory: distributed production system

After investigating microbial cellulose to the micro-scale of processes and material properties, as well as to the meso-scale of products, the following step is to explore the macro-scale of production systems envisioning future prospects for development and implementation. With this step the author is willing to answer one of the initial research questions: how can design contribute to foster the application and diffusion of biofabricated materials? And therefore, how can we make microbial nanocellulose rapidly available bypassing the long lead times which usually characterise the industrial development of new materials?
In this perspective design is characterised as connective tissue, exercising its ability to look at interconnections rather than shaping single products, acting at different scales moving from micro to macro – from process to material, from product to system. The goal is to provide a valuable alternative to industrial production through the implementation of a distributed system for microbial cellulose production and consumption, grounded on bottom-up practices. In this way, biofabricated materials are made available through everyday products, providing an easily and rapidly accessible alternative to synthetic materials, favouring at the same time a familiarisation and demystification process towards biofabrication and microorganisms with whom we collaborate, contributing to overcome fears, closures and preconceptions which often accompany what is new and unknown (Del Gesso & Trebbi, 2019).
When envisioning alternative systems of production-distribution-consumption, with the aim of shifting from the current one – linear and based on exploitation – to a circular one based on collaboration, we must remember that systemic changes can only be achieved through a radical change of frame. They are indeed the result of the accumulation of radical changes on the small scale (Manzini, 2018), of the discontinuity and disruption brought by radical innovation as opposed to incremental innovation (Norman & Verganti, 2014), which just brings improvements in continuity with the existing paradigms. To try to patch up con-

temporary issues without calling into question the whole system we operate in doesn't lead anywhere, since it does nothing but legitimise and repurpose the same boundary conditions which generated such issues. It ignores the intersectionality and interconnection among socio-cultural, environmental and economic issues, that are all the result of the anthropocentric view of the world, based on dominion, linearity and progress.
Therefore, in order to achieve real changes systemically, we need a radical shift in perspective, starting from revolutions on the small scale to be able to reach the global scale in the next future, counterposing collaboration to domination, circularity to linearity, evolution to progress.
A circular production system has to be necessarily grounded on the equivalence waste equals food. We need so to identify local nutrient flows and connect them to local companies and producers to develop a production system for microbial nanocellulose based on the *SLOC*[3] *scenario* (Manzini, 2015), and on the model of *distributed micro-production* – which can favour changes in behaviours, structures and processes, and "encourages the creation of alliances, communities and movements by modifying existing power relations" (Maffei & Bianchini, 2013).
The implementation of a diffuse micro-factory for microbial cellulose fabrication, will involve three main steps, described in the following paragraphs: the development of an operating model for a kombucha brewery; the design of a fermentation toolkit to support the replication of the model; and finally the scaling out of the model through the involvement of local stakeholders.

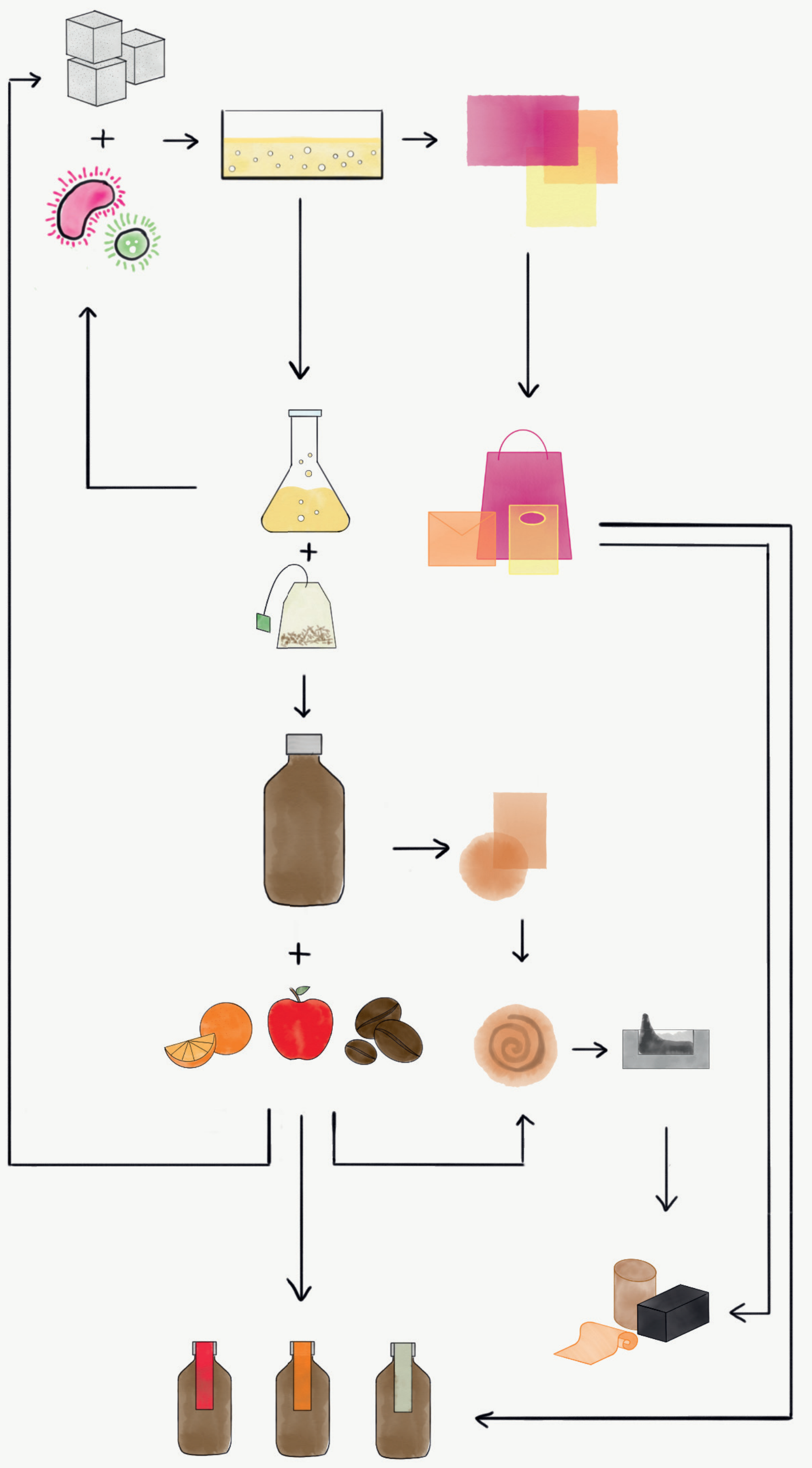
3. Small, Local, Open, Connected

6.4.1. S(co)bYio Design

The first step is the development of a zero-waste circular operating model for a kombucha brewery, designed for microbial cellulose fabrication.
For this reason the author started the project *S(co)bYio design*[4] in collaboration with Cultcha Kombucha, a kombucha brewery based in Amsterdam. The project is carried out through co-design activities involving students and professionals in the field of biotechnology, chemistry, economics and design, aimed at:
1. completely circularise kombucha production process,
2. increase the health benefits of the beverage,
3. self-produce microbial cellulose packaging and products.

Kombucha production had different byproducts. The main one is microbial nanocellulose, which can in itself be transformed into a new product. In addition, however, there are other typologies of raw matter available such as fruit peels, tea leaves or coffee grounds, waste of the ingredients used to flavour the beverage. Such organic matter contains important nutrients as sugars and tannins, which can be used to feed the microbial culture, and confer colour and smell to the final material. Otherwise, the fibres and powders can be mixed with microbial cellulose pulp for the production of composite materials.
In this way the company will able to self-produce its own packaging (labels, shoppers, etc.) and merchandising (flyers, business cards). Furthermore, exploiting the healing and dermocosmetic properties of the material, a product line for "inside out wellness" will be implemented, combining the benefits of the probiotic drink – which acts from the inside of your body–, with the one of the biofabricated material – which acts from the outside through skin treatments.

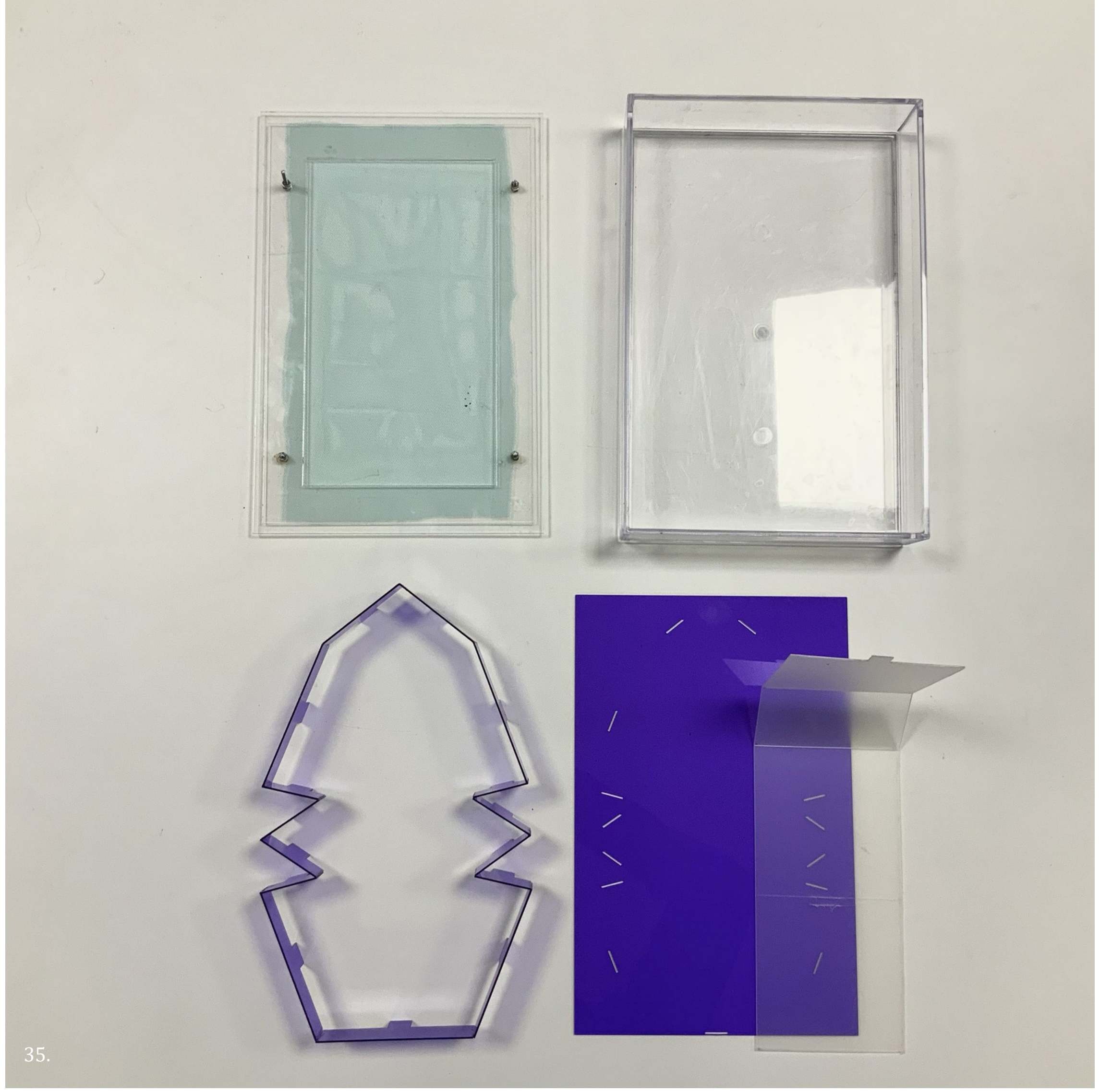
4. The project started in April 2020, in conjunction with the spread of COVID-19 pandemics. Due to safety concerns – since grounded on collaboration and teamwork, as well as tied to the physical dimension of the brewery – the stakeholders involved decided to temporarily suspend the activities, which have been resumed in March 2021



6.4.2. Fermentation Toolkit

The second step will consist in the development of a toolkit to support co-design practices. A toolkit is defined as “a set of tangible and intangible tools conceived and produced to make a specific task easier, so that even non experts can do it” (Manzini, 2015).
The fermentation toolkit will therefore include different tools which will facilitate the implementation of the proposed model, as is happening for plastic recycling with the “precious plastic” project described in chapter two, spread worldwide through open-source starter kits. The recycling communities born from the Precious Plastic spaces, acted as incubators for the birth of design companies and start-ups, which started to emerge after few years from the launch of the project as in the case of FOS Barcelona, who is producing recyclable eyewear from local plastic waste.
If we can’t act top-down by imposing any approach, mindset or behaviour, since we are interacting within complex interconnected systems, we can however create boundary conditions through which inducing behaviours and trigger virtuous cycles, thus affecting the socio-economic system with bottom-up practices, building from below an alternative grounded on regeneration rather than depletion.

The fermentation toolkit will consist in:
- a *Cookbook* collecting processes, ingredients and protocols to follow during fabrication;
- *Brewing tools*: containers and moulds shaped to grow the material directly in the desired shape;
- *Processing tools*: moulds to three-dimensionally shape the material during the drying stage, and moulds for casting nanocellulose composites.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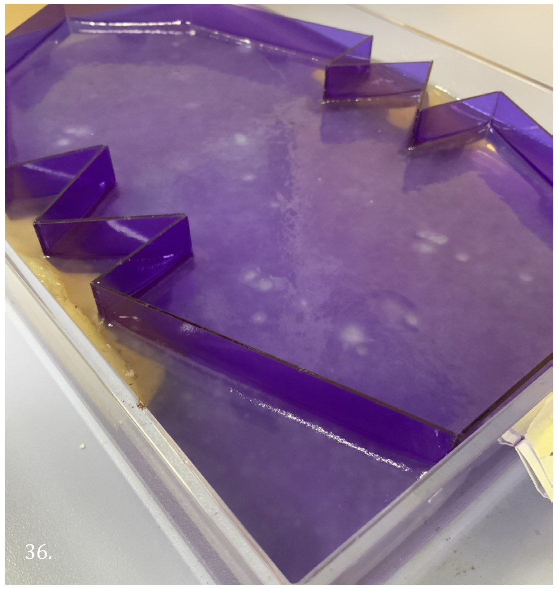
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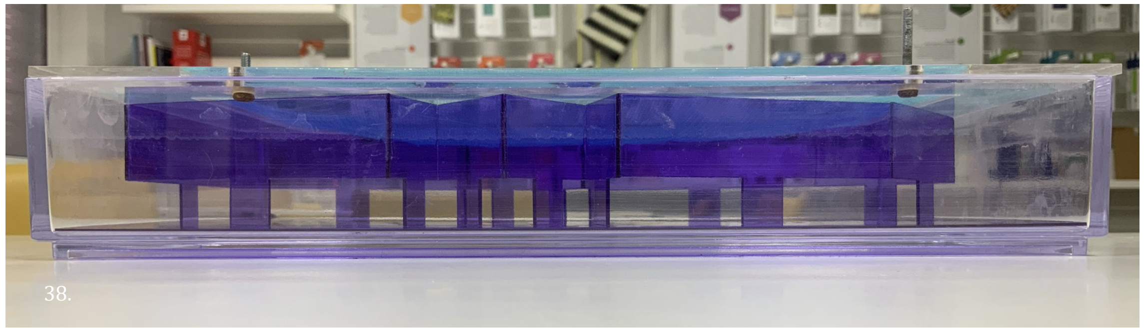
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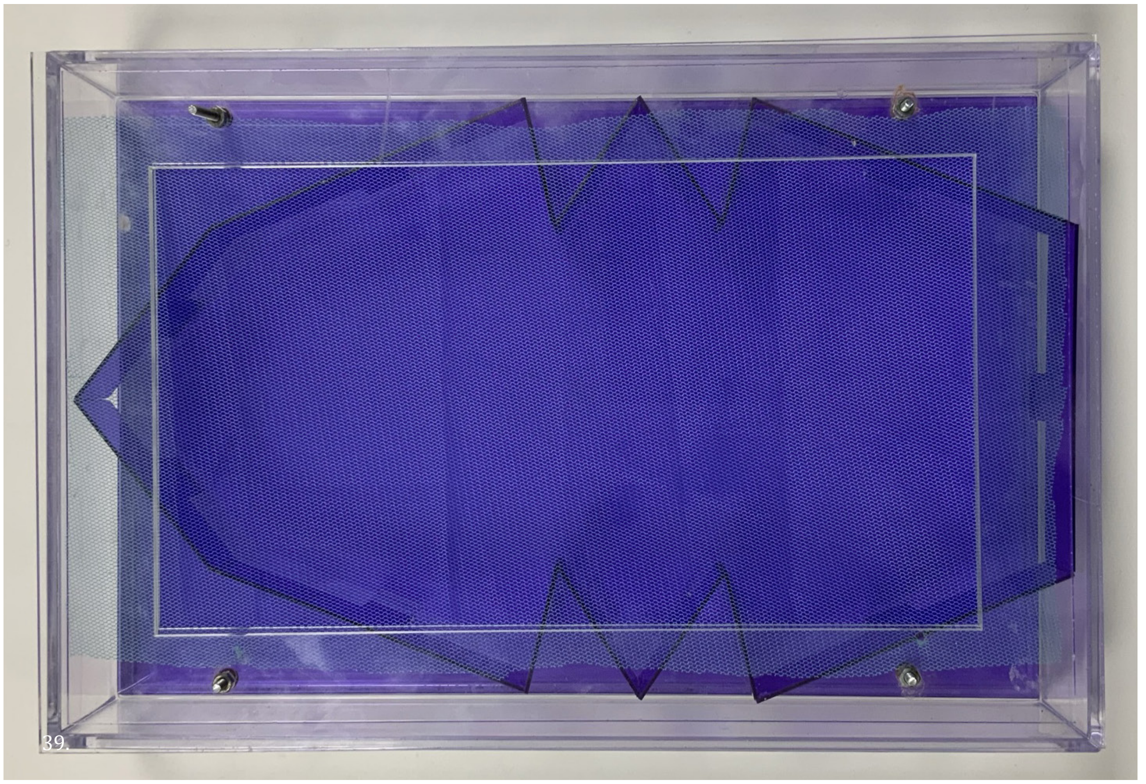
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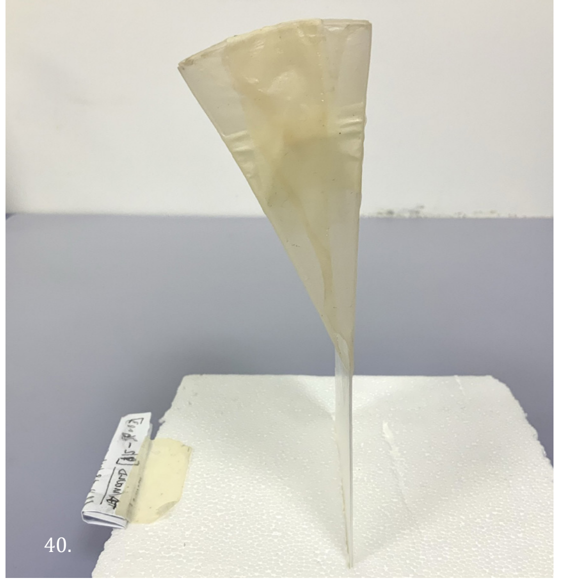
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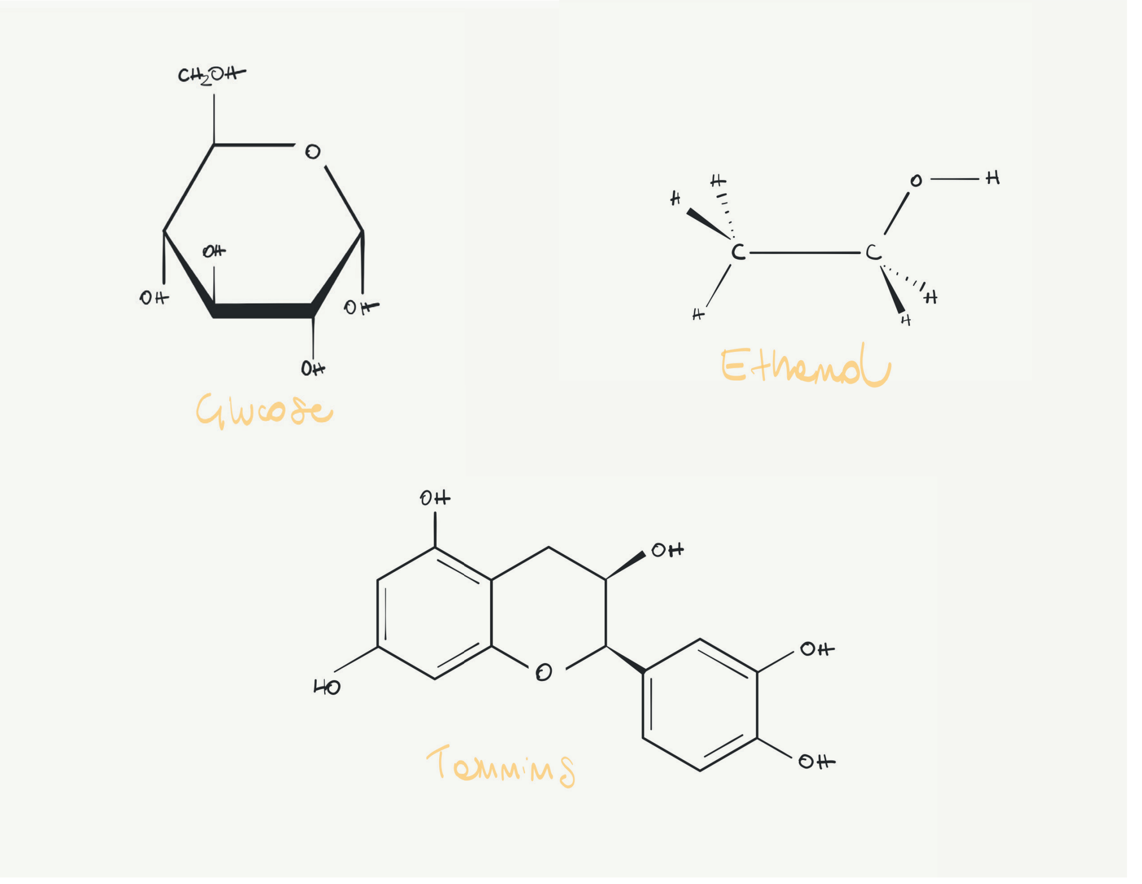
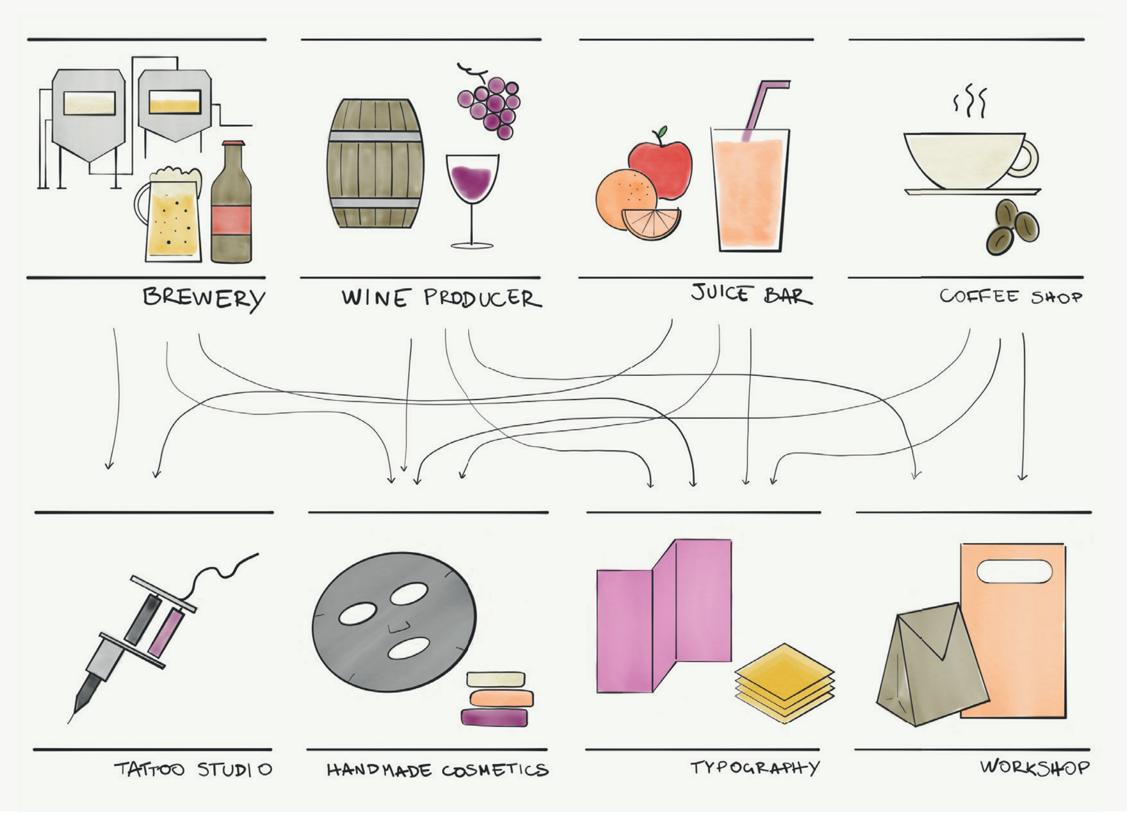
35. Packaging production tools: growing containers, fermentation moulds, drying moulds
36. Fermentation mould for packaging production
37. Moulded nanocellulose sample
38-39. Fermentation mould for packaging production
40. Drying mould: the harvested material is three-dimensionally shaped and left to dry

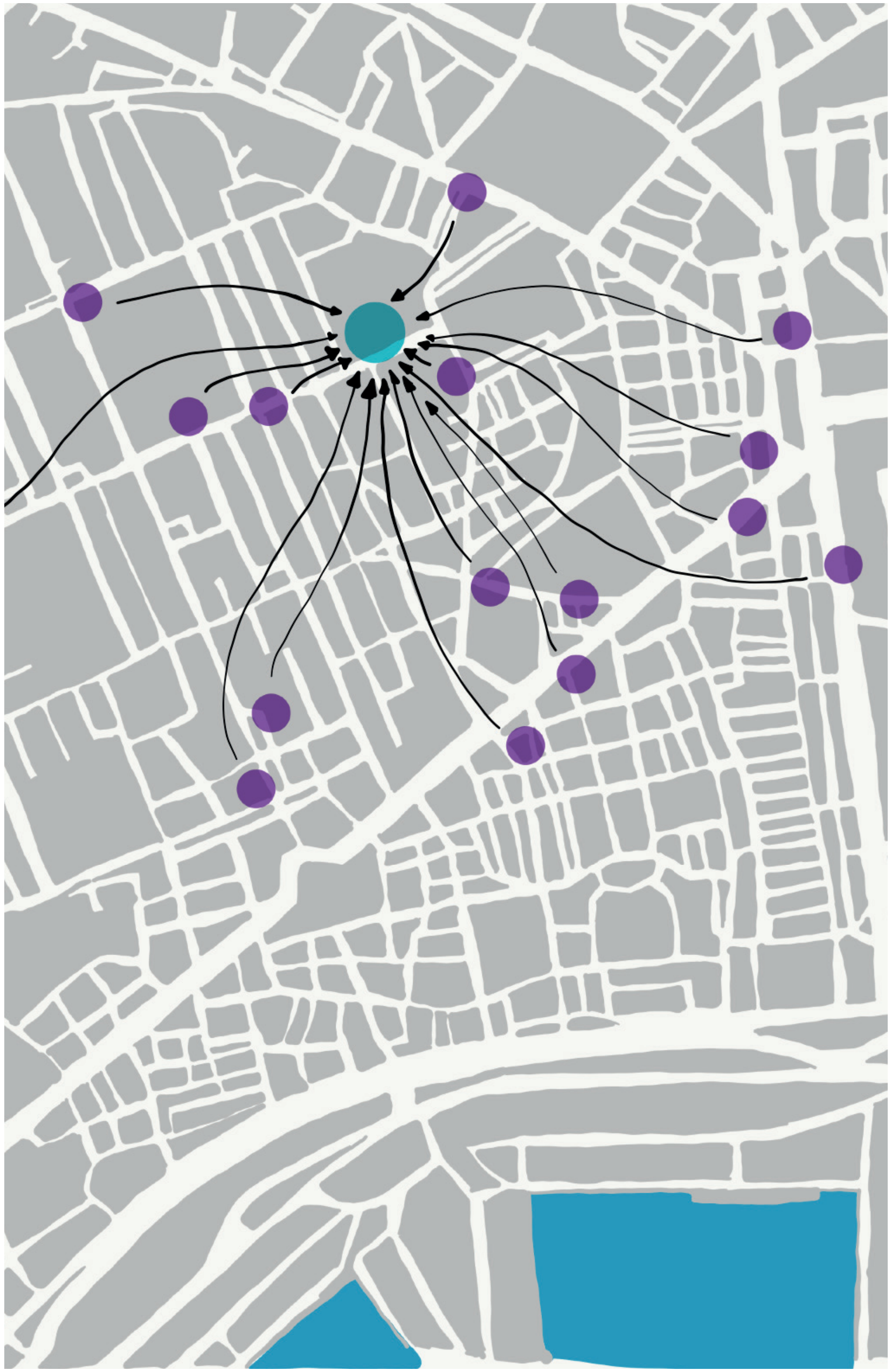
6.4.3. Horizontal Scaling

5. The social workshop is born as a spin-off of Samb & Diop association, from an idea of the architect and designer Riccardo Dalisi. It is located in Forcella neighbourhood in Naples, its activities are directed from the architect Marco Cecere and carried out from migrants and political refugees

The third and final step is aimed at multiplying the system developed in the first step with the aid of the fermentation toolkit, scaling it *out*, and therefore replicating the system within other contexts in order to be able to scale it *up* afterwards.
Through horizontal scaling the proposed model will be expanded to other typologies of food and beverages companies, according to the kind of waste they produce – containing sugars, ethanol or tannins. Hence, nutrient/waste flows characterising each specific territorial reality will be mapped and analysed, and subsequently connected with local companies interested in selling nanocellulose-based products. The companies, in their turn, will be selected according to the application scenarios previously identified – *augmented paper, sensory packaging, skincare*.
For example, byproducts from beer breweries, wine producers and any other alcoholic drink production, represent a valuable food source as well as any sugar source such as fruit peels from juice bars or food processing companies. On the other side, the stakeholders potentially interested to microbial cellulose retail can be found among tattoo parlours, handmade cosmetic stores, chemist's and herbalist's as regards *skincare*; typographies, stationer's and printmakers for *augmented paper* applications; and several typologies of small and medium enterprises for *sensory packaging*, from craftsmen and workshops to food and drink companies.
This step will involve the implementation of a pilot project, which will take place in the hearth of the city of Naples in collaboration with the social workshop *Avventura di Latta*[5]. The workshop, carries out artistic craftsmanship with poor metals for the production of jewellery and design artifacts. In the area surrounding the workshop there is an high concentration of coffee shops, which produce everyday huge amounts of coffee grounds – waste of the favourite beverage of most of the city dwellers. Such daily flow of raw organic matter can be collected and re-used to produce a tannin-rich culture medium for microbial fermentation, fed with sugar waste which is another waste/nutrient produced by cof-







41. Mapping nutrient flows: Avventura di Latta workshop and surrounding coffee shops, Forcella neighborhood - Naples

fee shops, although in smaller amounts. The microbial cellulose fabricated through coffee grounds fermentation, which from the perceptual point of view places itself somewhere between paper and fabric, will be used in the first place to produce cases, containers, labels and any other packaging required for the workshop's artefacts. Subsequently, once gained mastery over the material and its production process, a specific product line for microbial nanocellulose artifacts will be designed in line with the workshop core values.

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#kombucha&microbial cellulose

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PART III

Microscope & Macroscope

Making is Thinking

Richard Sennett

CHAPTER 7
CONCLUSIONS

ABSTRACT
The Future has always been associated with the idea of progress, resulting in the pursue for an exponential growth which is currently heading towards ecosystems destruction. Learning from Nature we can associate the idea of Future with the idea of evolution and evolve into a species able to live in symbiosis with nature, instead of progressing towards the path undertaken with the industrial revolution.
To do this, we need radical changes encompassing both cultural and technological spheres. Through design, the multiple aspects converging into the project have to be put to system and combined, no longer unpacked into a number of vertical specialisations – matter of study of other disciplines –, in order to provide an overall perspective which synthesizes such multiplicity into a whole. Through the project designers intergrate ideas and matter, experiential knowledge and envisioning ability, shedding light on the entanglement which brings together the micro and the macro scale.

7.1. Results and Findings

The research project investigated how designers are dealing with biofabrication, how such techno-scientific revolution is changing the design culture and how, on the other hand, designers' methodologies and approaches can affect the way biofabrication spreads and permeates our society.
Design research is unlikely to deal exclusively with design itself, usually its object of investigation involves other disciplinary fields, each of which has a different approach and perspective. The more our knowledge expands, the more the number and variety of disciplines converging in the project increases. In this case, with biofabrication, we are entering the scope of microbiology. Over the course of the research path, it has been repeatedly questioned what happens to designers and which role they play within such novel dimension of the project where disciplinary boundaries blur and skills intermingle. Therefore, the reflection arose from the following research questions:

RQ1 – How design places itself in the transdisciplinary dimension of biofabrication?
RQ2 – How far its range expands and which are indeed its limits?
RQ3 – Which is the contribution of designers in fostering the application, appreciation and consequent diffusion of biofabricated materials?

When trespassing into science labs, the greater risk is to slip out the horizontal transdisciplinary research, and fall into vertical hyper-specialisms. It would be a mistake to try to take the place of other professionals as biologists or materials scientists, doing poorly what others can do better. To implement a further compartmentalisation of knowledge within the design culture while the overall trend is in the opposite direction, doesn't make us more experienced nor more capable of moving among transdisciplinary research fields, on the contrary, does nothing but devalue the role of designers in a transdisciplinary team. Designers indeed, have to look at the variety of knowledge, know-how, methodologies and languages, and interpret them according to the specific reading key of design. It is essential to not abandon it in order to adjust to other methods and approaches, otherwise their figure has no reason to join such transdisciplinary fields of investigation. Designers mustn't act as hyper-specialists but learn how to dialogue with the multiplicity of knowledge fields involved, as well as with the different approaches and languages characterising them. They need to hybridise and contaminate methods and tools, but without demolishing the core elements characterising the design approach – induction, experience, trial and error. It is essential that designers get inside science labs to understand how to get around and fill the knowledge gap on several topics, since it's impossible to imagine and design without knowing. But it is likewise essential to maintain the specific design perspective, acting as synthetic element able to grasp interconnections and think long-range and long-term. Regardless of the specific research field and of the contaminations and collaborations which stems from it, designers remain designers and have to act as such, moving transversely keeping their specific contribution, therefore putting in connection the various faces of the project and the various skills involved.

The role of designers is indeed to envision future worlds and give such visions a tangible form through artifacts, always establishing a connection between the micro and the macro scale. To be able to do so, they will need to integrate two instruments: a microscope and a macroscope. "They are both needed to see things which escape our gaze: some because too big and complex, some others, on the contrary, because too small and specific" (Manzini, 1986). Using these two instruments, designers can bring scientific innovations and revolutions outside he laboratory and experimental dimension, and have an effective impact on the real world by relating them to all other aspects – social, cultural, environmental – with which they interact. Connecting the dots they can make visible the overall plan, overcoming specialisms and the partial views they provide.

To make this happen, design has to go back to its practical connotation, to the act of designing. Theoretical reflection can represent a starting point for the research but, above all, has to be the consequence of designing. Abstract theoretical speculation per se does not characterise the design activity – we are not abstract thinkers nor passive observers, just as we are not technologists not engineers. Designers can combine the practical and theoretical dimension condensing them jointly in the project, giving them a tangible form. Through design we can develop a theoretical reflection which arises from the concreteness of reality. Experience provides us with data from which we can build and develop the project, essential step to be able to deal with the contemporary world and look to the future.

To support the biofabrication revolution and design circular materials, products and systems, designers should downsize the space given to speculation that moves away from the concreteness and complexity of reality, and go back to getting their hands dirty – only true cognitive tool. Only by knowing how things work we can imagine and envision other possible futures, and therefore act to change route and head towards a symbiotic future rather that towards extinction. The abstract dimension of the project results indeed in unaware designs and designers, product of a mechanistic twentieth-century intelligence which looks at reality as a set of assembled parts, with objective properties and a deterministic linear nature. An intelligence compartmentalised into a myriad of sectors and disciplines, which sometimes talk to each other but always remaining separate independent entities, resulting into oversimplification and disconnection from the complex and interconnected world we live in.

Starting from the micro scale of biofabrication processes, and reaching the macro scale of natural-artificial ecosystems, we have the opportunity to design circular processes and transform human activities as well as the way we relate to the ecosystem, designing for regeneration.

After analysing the emergent fenomena of biofabrication from the point of view of materials, designers and industry, the research focused on a hands-on experimentation on microbial nanocellulose. The practical experimentation, grounded on the methodologies of Action Research and Experiential Learning, represented a pivotal moment for knowledge building and reflection, returning design research to the concrete dimension of making, where ideas and actions merge.

Throughout the experimentation it was possible to explore the material's identity, still vague and undefined, pushing the material to the limit, stressing it and interacting with its processes to be able to understand its potential, how it behaves and is characterised. Furthermore, this made possible to imagine its implementation into products, developing application scenarios able to valorise the specificities of the material. The experiential knowledge acquired within this stages, made possible to understand what can be actually done with this material, beyond the theoretical speculation about what we would like it to do – unable to bring actual results in real life. For example this is what happened when microbial cellulose entered the design world as microbial-leather, potential cruelty-free alternative to the impactful animal-leather, resulting however a poor substitute since equipped with totally different properties and behaviour. Designers don't have to invent something from nothing, but rather learn to read and listen to materials, and hence envision applications that suits them.

If we want to bring structural changes rather than symptomatic solutions, we need to match the techno-scientific revolution brought by biofabrication to a cultural revolution, integrating and hybridising the scopes of design and science. Designers have to merge the technological dimension to the environmental and cultural ones, otherwise the risk is to repurpose a new technology with the same wrong attitude of the past, therefore falling back into the same issues and problems of today.
To design with living matter brings important changes requiring a radical change of mindset. The temporal dimension is not anymore fixed, still nor eternal, but becomes cyclical, ephemeral and alive – it is born, grows and dies to be born again. It assumes great importance both in terms of processes – which have to adapt to and to respect nature's velocity for growth and disposal – and in terms of materials and products – which should evolve and transform over time, and cyclically go through ageing, decay and death as everything existing. This brings relevant change also in terms of aesthetics of materials and products, which becomes raw and imperfect, building a new language through which express the cyclical nature of life on Earth. It is up to design to communicate the value of imperfection and transience, discarding the idea of standardisation and aesthetic flawless of mass production. Understanding the way our world works, its laws and principles, also requires a radical paradigm shift on the ethical level, on the way we conceive ourselves in relation to other animal species and to other living systems, pushing us to shift from the anthropocentric perspective to an allocentric and systemic one. If humans in their collective actions have proved and continue to prove unable to give due weight to the climate and environmental crisis caused by human agency – which keeps implementing biodiversity destruction allover the planet –, the current pandemic crisis has shown us how wrong and short-sighted it is to think that what happens on the other side of the world won't touch us, what happens to other species won't touch us and what happens to nature in its complex won't touch us, since we are all part of the same whole.

Over the course of the research, the author collaborated with various institutions and facilities, thanks to which it was possible to examine in depth and test firsthand hypothesis and assumptions, besides providing an insight into diverse approaches and point of views. In particular, the hands-on experimentation was carried out at *Waag Society* in Amsterdam, which hosted and guided me in moving the first steps into the world of biodesign, also providing a perspective through which looking at the cultural and social implications of technology. The fermentation experiments continued in *SAPeri&co* fablab of Sapienza University in Rome, as well as in the microbiology lab of Prof. D. Uccelletti in collaboration with E. Schifano PhD, from *Biology and Biotechnology department* of Sapienza University. In addition to these research facilities, the collaboration involved *Slab Letterpress* in Rome for the printing experiments, *Cultcha Kombucha* in Amsterdam and *Avventura di Latta* in Naples, for the development and implementation of a diffuse micro-factory for microbial nanocellulose fabrication.

The research highlighted how design is able to bridge the different scales of the project acting simultaneously on perception, senses and emotions through material properties, on behaviours, semantics and values through products, as well as on environmental aspects as impact and circularity through resources, processes and productive systems. All of this wouldn't have been possible without diving into the world of fermentation, get acquainted with microbes as co-workers and get hands dirty. This is what enabled to acquire a knowledge of the material throughout the different stages of its transformation and an in-depth understanding of its generative processes and potential, something that the analytical study wasn't able to provide.

7.2. Possible Future Developments

To shape a post-industrial and post-anthropocentric society we need to learn how to fabricate, consume and more generally live discarding the destructive connotation that human activities have acquired over the past centuries. We don't have to take for granted that the only possible way is to fit into the industrial production model, grounded on the idea of incremental economic growth which opposes quantity to quality, and at the service of the global market oblivious of people and environment. We have indeed the possibility to envision new systems of production and consumption, questioning the founding principles and values of the current system.
We can imagine and implement rhizomatic models for distributed production, not hierarchical but decentralised and horizontal, made of multiple nodes which are part of a totality but at the same time potentially independent from it. Such model constitute itself as a dynamic network where new nodes and connections continually arise. It has to be designed for locality and be tied to the context, which brings an additional level of complexity, but without which is impossible to leave the abstract dimension and soak in the concreteness of real world.

The possibilities in terms of future developments of the research project, involve an exhibition for the dissemination of the results of the experimentation, addressed to both citizens and potential stakeholders to highlight the connective function of design, able to bridge research, production and society, as well as its ability to communicate the complexity of contemporary issues through artifacts[1].
As concerns the implementation of the diffuse circular production system, the activities with Cultcha Kombucha previously suspended for reasons of force majeure are now being slowly resumed. This will allow on one side to deepen the technical aspects of the fermentation process thanks to the support of microbiologists within the transdisciplinary team, and on the other side to develop more in detail specific concepts and products according to the macro application scenarios envisioned for microbial nanocellulose.

1. The exhibition was intended to take place during the PhD, however this was not possible because of the safety measures which stopped all public events in Italy as in many other parts of the world

Thanks to the ongoing collaboration with Avventura di Latta, the author aims at putting into effect the horizontal scaling operation described, so to test its limitations and problems in order to improve and perfect both the toolkit and the proposed production model. The project aims to co-design together with the workshop's craftsmen a tailored packaging line for the jewellery and artifacts they produce, translating the strong relationship with the territory and the use of "poor" materials which already characterise their production into the packaging material through its sensory properties – determined by the kind of nutrients used in the fermentation that in this case will be coffee grounds, waste of the cult drink of the city. Thanks to the facilities and craft skills provided by the workshop, elements and moulds will be realised in order to shape the growing material according to the kind of packaging to be produced. Some of the spaces of the workshop will be reconverted into a vertical micro-factory to make them completely autonomous for the packaging production. Once gained a sufficient knowledge over the process, it will be possible to go beyond the packaging self-production and develop microbial nanocellulose product lines.