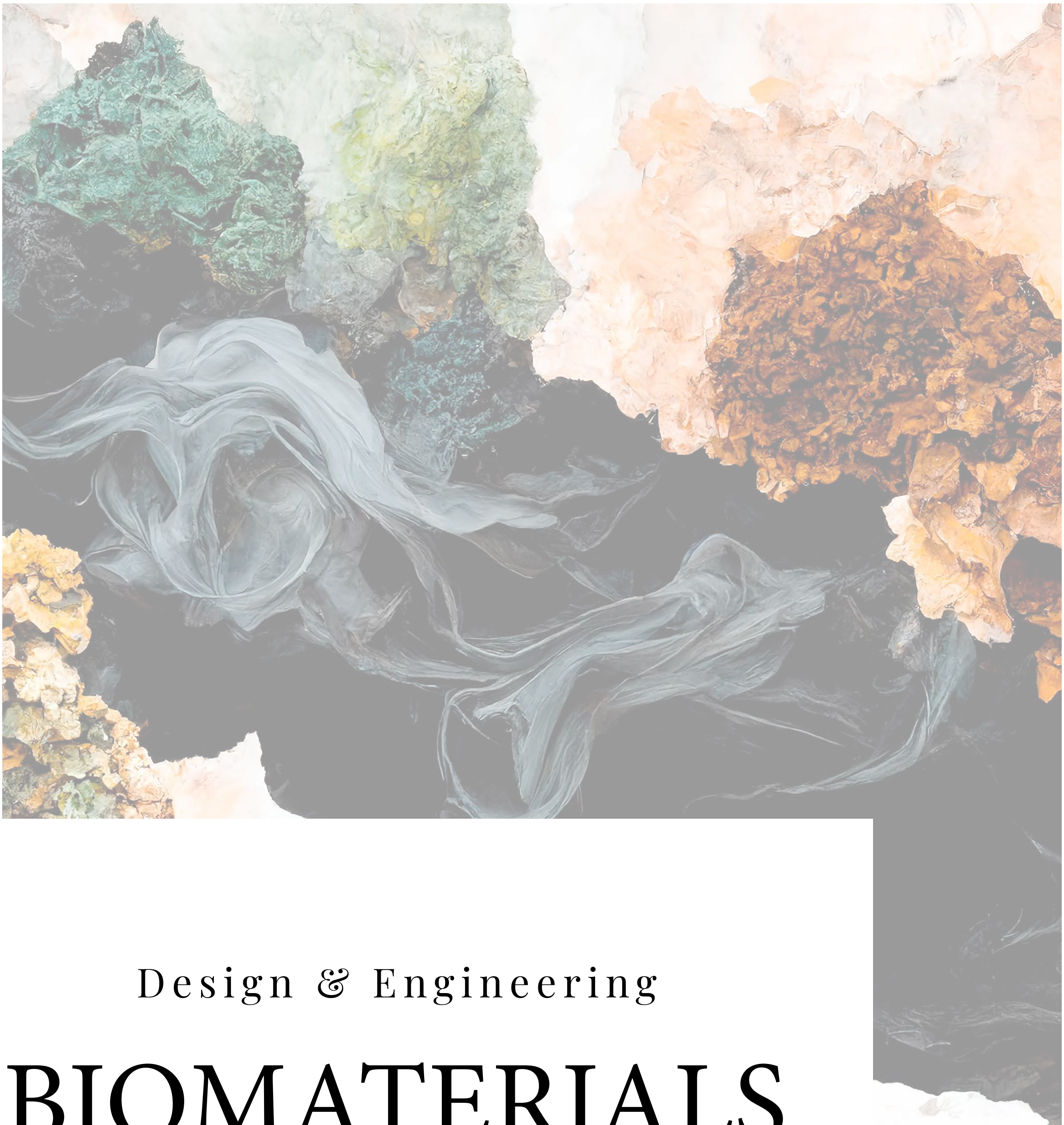


Design & Engineering

BIOMATERIALS

Circularity within reach of all

Nicolás Peña Rodríguez

Table Of Content

Author:
Nicolás Peña Rodríguez

Supervisor:
Maria Rita Ferrara

Co-supervisor:
Alessandro Squatrito

Submitted in fulfilment of the requirements for the degree of:
Master of Science in Design & Engineering

Design & Engineering
Department of Design
Politecnico di Milano
2022-2023

POLITECNICO
MILANO 1863

CHAPTER
ONE

Introduction

1.1. BACKGROUND

The notion in which the industry is producing and people consuming has been generating concerns on the sustainability of our evolution as a species. Climate change is an ongoing concern where both scientific, academic, and industrial areas have been trying to tackle by educating consumers, creating new and sustainable products, while modifying production and disposal cycles. During this process, it has been understood that no individual effort is enough to give solution to this issue, a solution must comprehend all the different actors involved in the consumption chain, from the ideation, design, prototyping, production, consumption, and disposal of the same.

The linear production and consumption model after the first industrial revolution, where natural and social capital is harvested to create financial and productive capital (Senge & Castedt, 2001), has been problematic to the long-term livelihood on earth due to the contamination and over production of goods that are consumed. Programmed obsolescence, fast fashion, fast food, all successful and profitable business models that, in the long run, are not sustainable for the planet, have been dominating the way the economy runs. Due to their effects, the world has started to move into different strategies that aim to attenuate these unsustainable practices, such as recycling, waste managements, development of new materials, circular production processes, consumer education, brand awareness, and more.

This thesis paper aims to analyze, expose and exemplify the different issues that involve the strategies seeking to tackle the matters previously stated, focusing greatly on Circular Economy and Design for Sustainability. Biomaterials, understood as a subtopic of these models, appears as a research subject that seeks to provide an alternative for inquinating and polluting materials, through scientific and design (experimental) exploration. Additionally, this thesis will be focusing on understanding the scope biomaterials have in a Circular Economy and Design for Sustainability models, through hands on experimentation and literature review of different examples that addresses the topic in different matters, considering different materials, products, processes, and production tools, developed in an amateur to semi-industrial environment.

On the following sections, a description of the general and specific objectives of this research thesis will be exposed, showcasing the context in which it will be developed and pointing out its significance.

1.2. CONTEXT

This study was developed in Milano, alongside the hand of the research department of Design and Engineering, and the fabrication laboratory Opendot, with the scope of broadening the understanding on a trending topic such as Circular Economy, Design for Sustainability and Biomaterials. The project is directed to entrepreneurs, designers, artisans or small companies that want to incur in the world of biomaterials, aiming to update their products or produce new ones, moving towards a more sustainable economic environment.

1.3. PURPOSES

General objective

Develop a research project on self-made biomaterials, considering circular design practices, focusing on proposing tools and methodologies that allow the production of semi-finished and/or finished products.

Specific objectives

- Develop a thorough study analysis of biomaterials, design for sustainability and circular economy, tools, products, and processes, both industrial and homemade, that provide a complete overview of the technological state of the topic.

- Research through experimentation and literature the tools and skills needed for the development of biomaterials, while stablishing procedures to develop a finished or semifinished product made out of biomaterials.

- Develop a prototype tool through digital fabrication methodologies that aid in the fabrication process of a finished or semi-finished product made of biomaterials.

- Develop a prototype material, suited for the fabrication of semi-finished or finished products.

- Stablish key insights during the development of fabrication of biomaterials that help the reader understand the limitations, benefits and considerations when working with them.

- Screen and analyze several by-products, stating their benefits, limitations, and considerations, taking into account their method of obtention, processability, manufacturability, and economical context.

- Develop a set of finished products made out of biomaterials, through the use of digital fabrication procedures, tools and machinery.

This study was developed in Milano, alongside the hand of the research department of Design and Engineering, and the fabrication laboratory Opendot, with the scope of broadening the understanding on a trending topic such as Circular Economy, Design for Sustainability and Biomaterials. The project is directed to entrepreneurs, designers, artisans or small companies that want to incur in the world of biomaterials, aiming to update their products or produce new ones, moving towards a more sustainable economic environment.The notion in which the industry is producing and people consuming has been generating concerns on the sustainability of our evolution as a species. Climate change is an ongoing concern where both scientific, academic, and industrial areas have been trying to tackle by educating consumers, creating new and sustainable products, while modifying production and disposal cycles. During this process, it has been understood that no individual effort is enough to give solution to this issue, a solution must comprehend all the different actors involved in the consumption chain, from the ideation, design, prototyping, production, consumption, and disposal of the same.

The linear production and consumption model after the first industrial revolution, where natural and social capital is harvested to create financial and productive capital (Senge & Castedt, 2001), has been problematic to the long-term livelihood on earth due to the contamination and over production of goods that are consumed. Programmed obsolescence, fast fashion, fast food, all successful and profitable business models that, in the long run, are not sustainable for the planet, have been dominating the way the economy runs. Due to their effects, the world has started to move into different strategies that aim to attenuate these unsustainable practices, such as recycling, waste managements, development of new materials, circular production processes, consumer education, brand awareness, and more.

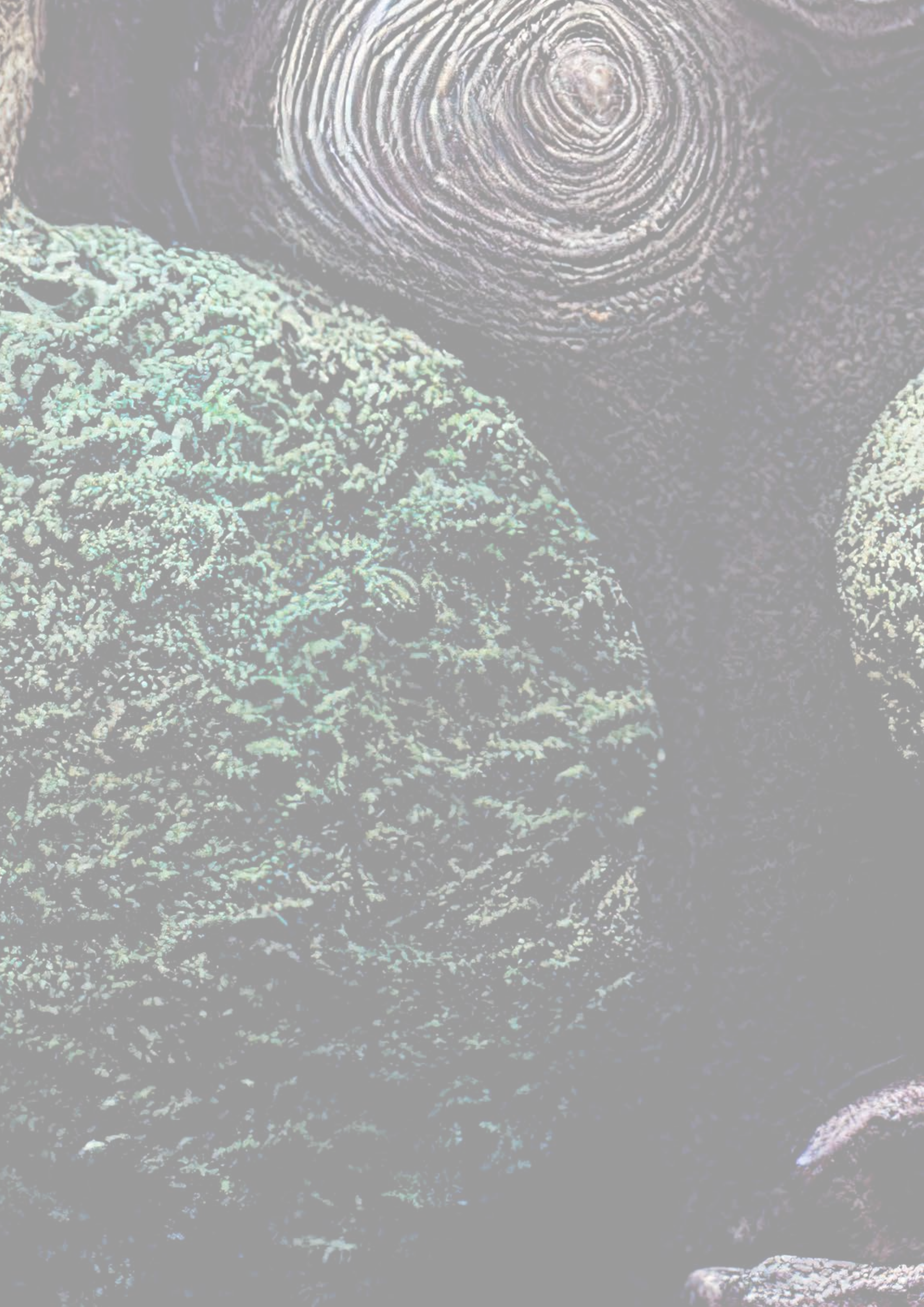
This thesis paper aims to analyze, expose and exemplify the different issues that involve the strategies seeking to tackle the matters previously stated, focusing greatly on Circular Economy and Design for Sustainability. Biomaterials, understood as a subtopic of these models, appears as a research subject that seeks to provide an alternative for inquinating and polluting materials, through scientific and design (experimental) exploration. Additionally, this thesis will be focusing on understanding the scope biomaterials have in a Circular Economy and Design for Sustainability models, through hands on experimentation and literature review of different examples that addresses the topic in different matters, considering different materials, products, processes, and production tools, developed in an amateur to semi-industrial environment.

On the following sections, a description of the general and specific objectives of this research thesis will be exposed, showcasing the context in which it will be developed and pointing out its significance.

1.4 Significance

This research is important to close a technical and knowledge gap for designers, young companies, and entrepreneurs that want to incur in the world of biomaterials, providing guidelines, examples, and tools (both physical and written) for them to generate usable, reliable, and even sellable products.
The development of the final product will be used as a way to exemplify and show, not only the capabilities of the material developed, but of the tools and processes used to create it.

The following chapters will expose a critical evaluation of the design and scientific literature found, showing a synthesis of the information, and pointing out the key authors that have treated similar arguments. This chapter will be divided in the 4 main topics that will guide the research: Biomaterials, Circular Economy-Design, and Do-It-Yourself (DIY) practices.



CHAPTER
TWO

Biomaterials

2.1. INTRODUCTION

"A biomaterial is a systemically, pharmacologically inert substance designed for implantation within or incorporation with a living system." (Park, 1984)

Although the definition of biomaterials can be widely arranged, from chemical, pharmacological and biomedical applications to art, fashion and science contexts, when defined for all of them terms such as natural, incorporation, cohabitation, function replacement, biocompatibility, come to coalition. For this paper due to its accuracy but also simplicity, the definition of a biomaterial will be considered as: A material specifically designed to interact with nature (PennState, 2020), therefore, not harming it, not polluting it, but coexisting in a harmonic way. For this thesis the main experiments were made with materials coming from natural by-products, such as eggshells, coffee waste, grass, spices, and finally sawdust.

Biomaterials were born as a response to the contaminating practices the world has been suffering and as an answer to contaminating materials, such as plastics and their derivates. The idea of producing a material that can be both sturdy and sustainable is starting to be demanded by the consumers and therefore having to be implemented by the producing companies. This chapter will provide an overview to the reader about the different examples of biomaterials that can be found, how they have been implemented in the industry, their main composition, and different processes with which can be manufactured.

2.1. CATEGORIES

Biomaterials can be segmented into two big categories, the first one, regarding their composition, meaning the origin or ingredients which compose them, and secondly their way of development, indicating if they are manufactured, recycled, or grown.

The composition or origin of the materials are commonly divided between animal and vegetable, indicating where their main ingredients or base come, either from an animal or vegetable source. The following sections will exemplify both of them.

2.2.1 Animal based

Let us start with Bioplastic skin (Steinars V. , valdissteinars, 2022)is a first example for animal derived biomaterials. Valdìs Steinars, an Iceland materials designers developed this project where its aim is to replace the packaging of meat products with materials from the same animal its being packed in. Bioplastic skin is a bioplastic made from the actual skin of the animal its being packed. With the same idea of profiting from the entire piece of animal, if being sacrificed, Steinars has developed more projects getting to exploit all the possible by-products from the same. From stained horsehair to tableware made from bones (Steinars V. , valdissteinars, 2022), all these projects explore the idea of generating a new material from animal waste, giving a new life to a commonly discarded product.

Moving to another example, we find Shellworks, a company that has been developing over the past years a packaging solution made from shellfish waste, to replace plastic in the cosmetic industry. Shellworks started also by experimenting with thin plastic like material derived from crustacean shells (shellworks, 2022). For these second example, a resemblance within the texture and color of the material can be directly linked to its source (Shellworks, 2019). In a similar approach, Jeongwon Ji, a student from the Royale College of Arts, studied the extraction of chitin polymers from crushed crab shells of the Chinese Mitten crab specifically an unwanted invader crab species, to develop cavsings for electronic products (Royal College of Art, 2013). ed invader crab species, to develop casings for electronic products (Royal College of Art, 2013).

Image 1. Picture of Bioplastic skin project from Valdìs Steinars, wrapping a piece of meat (Steinars V. , 2022)

When thinking about animal-based biomaterials, is inevitable to ponder ta subtle incoherence

Image 2. (1) Biopolymeric caps from Shellworks (shellworks, 2022), (2) Initial Shellworks experimentation cups, from crustacean shells (Shellworks, 2019), (3) Chitin polymer experimentation (Royal College of Art, 2013)

in trying to reduce plastic use but using animals to replace them. Well, this isn't always the case. During their live cycle, animals pass through different stages where residues or, let's say, by-products, can be left, either when they age or die. For example, in Deutschland when the mealworms transform into beetles, and when these die, they leave a peel or armor which becomes waste. Deutsch designer Aagje Hoekstra was able to profit from this residue and use its chitin richness to develop a beetle-shell-based bioplastic. Hoekstra was able to benefit from the beetles' waste and produce a material useful to produce jewelry and decorative pieces (Dan Howarth, 2013).

When thinking about animal-based biomaterials, is inevitable to ponder ta subtle incoherence in trying to reduce plastic use but using animals to replace them. Well, this isn't always the case. During their live cycle, animals pass through different stages where residues or, let's say, by-products, can be left, either when they age or die. For example, in Deutschland when the mealworms transform into beetles, and when these die, they leave a peel or armor which becomes waste. Deutsch designer Aagje Hoekstra was able to profit from this residue and use its chitin richness to develop a beetle-shell-based bioplastic. Hoekstra was able to benefit from the beetles' waste and produce a material useful to produce jewelry and decorative pieces (Dan Howarth, 2013).

Now, animal-based biomaterials don't necessarily always have to be made out of animals, of their wastes or of their parts. Tomas Libertiny's Eternity can be proof of this. In this case, the sculpture made by the Slavic design-engineer Tomas Libertiny is crafted and manufactured by bees. For this piece, Libertiny designed a 3D printed case of the bust of Nefertiti, the Egyptian Queen, where bees were able to work, and construct a honeycomb which eventually will be filling and 'sculpting' the piece. The piece required 60,000 honeybees and a total of 2 years to being completed. This is an example of the possibilities of how nature and design can be combined to produce art.

Lastly, another interesting project related to animal-based biomaterials is Wiggy, a biodegradable dressing table. As is known, us humans enter in the category of animals too, where Wiggy comes in as a dressing table made of pressed human hair mixed with polylactide acid (PLA). The project is born as an exploration of urban waste, leading to discover the abundant and unused human hair clippings, leading to a rather interesting, innovative, material development (Bondar, 2018).

Image 3. (1) Beetle shell bioplastic by Aagje Hoekstra (Dan Howarth, 2013), (2) Human hair pressed hair chair (Bondar, 2018) (3) Thomas Libertiny's Nefertiti (Libertiny, 2020)

2.2.2 Vegetal based

In the same way animal-based biomaterials had different ways of development, growth and building, the vegetable-based biomaterials do too. Now, certain materials are always present when speaking about vegetable biomaterials, like vegetable gelling agents such as agar-agar, algae, cellulose and more. These ingredients are widely present in these types of biomaterials since they allow to solidify and generate polymeric chains to produce bioplastics or resins. These specific ingredients will be analyzed more in depth in chapter ***2.3 Biopolymers – A technical overview.***

Understanding that vegetable biomaterials are vegetable or plant based it can be deduced that for example, polylactide acid (PLA) is a biomaterial. And yes, it can be defined as such, but it lies on the misconception and on the scope that the biomaterials analyzed search to be preferably compostable. Having said this, let's stop for a moment and analyze these materials further.

2.2.2.1 Vegetal-based - Bioplastics

PLA is a plastic derived from renewable sources most commonly from corn or sugar cane. The starch extracted from the renewable sources is passed through a process called enzyme hydrolysis, obtaining glucose which then, by fermentation will produce lactic acid. This lactic acid will then go through processes of condensation and polymerization to finally become PLA (Chae Hwan Hong, 2012).

Now, although PLA comes from a natural source and it's an alternative to its petroleum equals, it poses a constraint in its disposal and waste management. PLA, although is marketed as biodegradable, is not compostable. For the PLA to degrade it needs to be at a temperature between 55º-70ºC, under controlled humidity and in the presence of specific micro-organisms, conditions that can mainly be found in an industrial composting plant. All these means that if left on the ocean or in a landfill, without the men-

Image 4.(1) Plants from Plants Lego set (LEGO, 2022)., (2) Center table from botanical series (LEGO, 2023)

tioned required conditions, a PLA piece will take around 80 years to decompose, therefore imposing a similar contamination problem regular plastic such as ABS already impose (Valdivieso, 2019).

As PLA, there are other bioplastics made from renewable and vegetable sources that aim to move away from oil extraction processes. A current example comes from the LEGO's project Plants from Plants. An initiative from the LEGO Group to move to a more sustainable approach on diversifying the type of plastic they use, reaching plant-based plastics. The Plants from Plants material, as LEGO states, is processed from the sugar cane, a resource able to produce bio-polyethylene going through a fermentation process to obtain firstly ethanol, a dehydration process to obtain ethylene, which is further polymerized to obtain the plastic in mention. Once again, this plastic, although obtained from a renewable resource is not biodegradable (LEGO, 2022). This new approach allowed LEGO not only to start moving away from the oil-based plastics, but opened the opportunity to launch their Botanical series, a series issued for an adult audience which can be described as plant lovers. It allowed the company to diversify their core products enforcing their sustainable message.

For the research purpose of this thesis, it is important to clarify the conditions biodegradable plastics such as PLA or bio-PE impose, without the intention to undervalue or dissuade the use of these plastics. Going forward with the research there will be several examples of biomaterials, that for their development use PLA, therefore it is important to clearly understand its properties, characteristics, and condition of biodegradability, handling, and waste management. Another important issue to uphold is that the development of research materials, as already been said, seeks an alternative to these types of contaminating plastics. The following

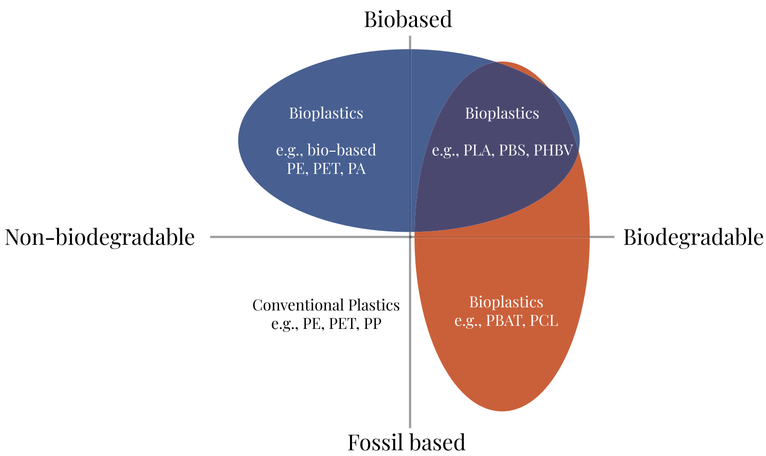


Image 5. Different properties of plastic materials regarding their biodegradability and origin. (Bioplastics Europe, 2022)

Image 6. (1) Extraction of blue berry dye used for colouring bioplastics (2) Coloured bioplastic straws (3) Cookie packaging from light violet bioplastic

graph showcases additional information regarding the condition of biodegradability of some of the most common plastics, which showcases how also even bio-based plastics can be non-biodegradable.

Moving towards different proposals its Margarita Talep, an industrial designer from Chile, that upbrings different vegetable-based proposals for bioplastics. Her research of desintegra.me aims to tackle the problem of single use plastic, basing herself on the hypothesis of: "... if the average lifespan of these products [plastics of single use] do not go over the 50 minutes, then why these disposable products are made from an indestructible material?" (Talep, 2017). In her projects Talep develops different proposals of bioplastics and bio pigments to substitute disposable spoons, wrapping paper, packaging, straws, and even presentation cards. For the development of these plastics, she uses a base from algae extracted components, which renders soluble the material when dipped in water, while for the pigment, she extracts natural dyes from fruits, vegetables or even spices, like blueberries, turmeric, or cabbage.

Another example that uses seaweed as their base material for bioplastics fabrication is Notpla, a sustainable packaging startup that develops biodegradable containers to replace conventional plastics. Notpla is known for their development of Ooho, an edible and fully biodegradable sachet, that replaces water bottles or plastic sacks, breaking the gap between product and packaging. It is interesting how the design approach went forward to create a new user experience, changing completely the way of consumption, of water for example, where when consuming the product, the same packaging can be eaten. This adds value not only on an environmental scale by avoiding generating waste (since the packaging will either biodegrade or be eaten), but on an experiential level by providing the consumer with a different sensorial experience.

Image 7. Notpla sachet packaging of different drinkable liquids (Notpla, 2022)

2.2.2.2 Vegetal based grown materials

Straying away from manufactured vegetable-based biomaterials there can also be found different ways in which biomaterials can be made, or in this case grown. There are different ways in which materials can be grown, in fact natural materials already widely used like cotton and silk re harvested from either plants or insects to develop a usable material. Although growing materials is not a new habit for humanity, the offer is limited meaning that not all grown materials have the suitable properties to replace already common materials such as plastics, leather, or even wood. Alternatives such as mycelium have been promising for grown products category due to its versatility, sustainability, and accessibility.

Mycelium is part of the fungi kingdom and is the network of threads, called hyphae, from which mushrooms grow (Mylo, 2022). The material itself is developed from this network of threads where, by the help of a bio-substrate (wheat, grass, seeds) and food for the mycelia (usually starch) the mycelium grows intertwining with the substrate, generating strong bonds building a solid piece. This piece will be then baked in an oven to neutralize the mycelium and stop it from proliferating to generate a final solid strong piece. This process can be aided with baking molds to give a defined shape to the final semi-fabricated material. This latter is one of the many processes to manufacture a material from mycelium, where it can take a solid shape, a flat sheet like shape, it can also be edible if mixed with the right substrate and type of fungi. It is important to notice that all fungi have a form of mycelium, so as many types of fungi there exists the same number of alternatives there are to generate a different piece.

Image 8. Land section showcasing the growth of Mycelium (Mylo, 2022)

There are several companies that have been developing ready-made products with this material. MOGU, for example, is an Italian company that develops acoustic isolating panels and floors from mycelium. The company profits from the soft texture, the isolating properties, sturdiness, and the way of molding of this material to propose a design line of organic and soft shapes for their panels.

The panel inner structure is formed with an already dried mix of mycelium plus substrate, which is molded to obtain the desired shape. The panel is covered and closed by a leatherlike recycled fabric of soft and pastel colors, allowing to showcase and portray the naturality of the piece.

Image 9. (1) Mycelium tile samples (2) Sound isolating panels made from mycelium (MOGU, 2022)

Another common product developed from this material is synthetic leather. Mylo profits also from the properties of this material where instead of using a mold or a substrate to make it solid, they mix it with a plasticizer and then hot press it to generate a sheet-like piece (Elsacker, 2018). They later tan it and dye it, giving the desired color. Mylo's leather like material is manufactured by one of the biggest companies to date on the development of mycelium products, Ecovative.

Ecovative is possibly one of the biggest companies that produces, manufactures, and commercialize products made from mycelium. From leather, packaging foam and finally food, Ecovative is one of the companies that truly showcase the versatility of this almost magical material. Ecovative, apart from the already explained leather like material they developed a technology called AirMyceliumTM, where they can simulate a soil-like environment in air chambers allowing

Image 10. Section views of the isolating panels samples made of mycelium (MOGU, 2022)

Image 11. Synthetic leather made of mycelium (Mylo, 2022)

the mycelium to grow upwards, creating a pillow-like material. From this, the foam can either be used for packaging, stuffing or even pressed and be eaten as vegan bacon.

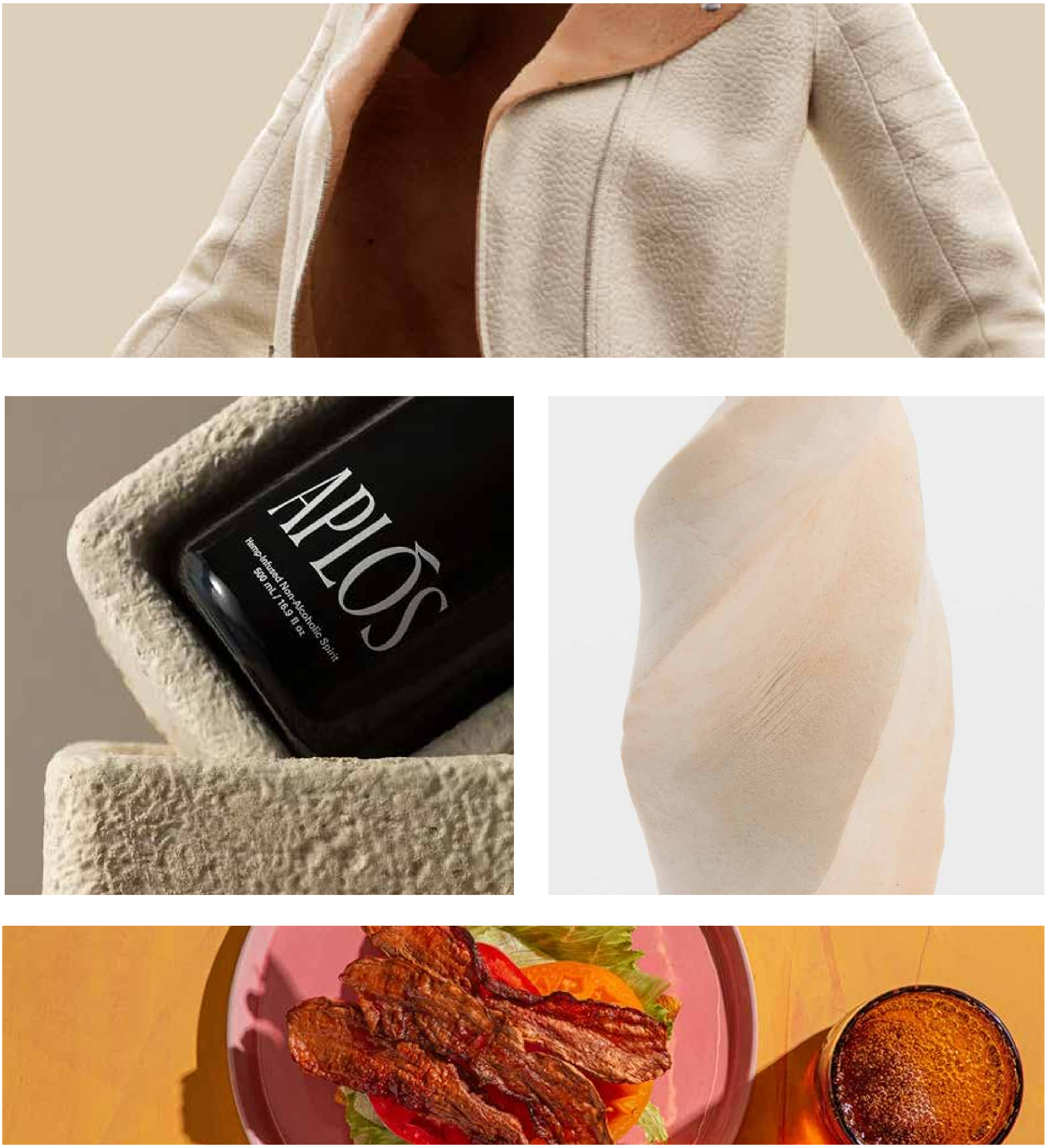


Image 12.Different applications for the AirMyceliumTM technology (1) Jacket made of Mycelium leather, (2) Packaging, (3) Foam, (4) Vegan bacon (Ecovative, 2022)

There are other growing processes with a less chemical approach and more artistry one. In this case, Full Grown, a company developed by Alice and Gavin Munro, explores the idea of how nature can be the craftsman for an actual product. Full Grown reconsider the manufacture with the bio-facture, creating furniture from the natural growth of trees, a similar example as the one seen of Tomas Libertiny with its bees, where nature, in this case trees, are building the finished product. The process that undergoes these chairs is possible by a metal frame designed to guide the growing tree into a desired shape, where after 6 to 9 years of growth, the piece is then chopped dried, trimmed, and polished to be sold (Fullgrown, 2022). As understood, the growth process and time span of bio-facturing is a limiting, making these more than a commodity, a luxury, reaching a cost from £5,000 to £12,000 (Wilkes, 2018).

Image 13. (1) Finished Fullgrown chair (2) Crop of Fullgrown chairs being harvested (Fullgrown, 2022)

2.3. BIOPOLYMERS - A TECHNICAL OVERVIEW

The purpose for this thesis is to analyze and experiment with recipes, materials and tools needed to manufacture biomaterials from a semi-professional (DIY) point of view developing an actual tool and a set of guidelines to process biomaterials to obtain usable semi-finished or finished products. As seen in the previous section, there are several ways of either growing, crafting, mixing, or manufacturing a biomaterial, where analyzing and experimenting with all of them can be impractical. Now, considering a circular design approach must be integrated within the research, making use of a by-product made the most sense. Making use of a recipe or a biomaterial that profits from a by-product as either a base or an additive, working with vegetable-based bioplastics was the most appropriate choice.

Although there might seem a lot of different bioplastic recipes, all share a similar base structure, composed by a gelling agent (or a polymeric base), a plasticizer, a filler, and a solvent. Each of these elements have a certain function on the whole recipe, where changing its proportions may change considerably the final product, modifying either its mechanical, chemical, and even electrostatic properties. Let us define and exemplify for the latter components:

2.3.1 Polymers (Gelling agents)

To start digging into the processes of bioplastics and to have a better understanding on what type of products are being made, it is important to start by defining what polymers are and what the polymerization process does. A polymer is

Polymer

Plasticizer

Matrix

Solvent

any class of natural or synthetic substance composed of large molecules, which are composed of simpler chemical units called monomers. For example, solid parts of the plants are made from polymers, such as cellulose, lignin and other resins (Britannica, 2022). As for the biomaterial's recipes, polymers can be defined as the gelling agents, or the ones that agglomerate the material and give it the base structure.

As known, many of the synthetic polymers, although applauded by their mechanical and chemical properties, such as nylon, polyethylene, polyester, Teflon, or epoxy, are not biodegradable, therefore not sustainable, and not suited for a biomaterial development purpose. Thankfully, nature is already a provider of different types of polymers that can be used for the manufacturing of bioplastics, being biodegradable. The article of Natural-based plasticizers and biopolymer films: A review clearly segments the different types of biodegradable materials in the following way (Vieira, Gurgel, & Altenhofe, 2010):

a- Polymers from biomass, such as agro-polymers:

i. Polysaccharides like starches (wheat, potato, corn), ligno-cellulosic products (wood), and others (pectin, chitosan/chitin, gums).

ii. Protein and lipids, coming from animals (casein, whey, collagen/gelatin) and from plants (zein, soya, gluten).

b- Polymers obtained by microbial production, such as polyhydroxyalkanoates (PHA) such as poly(hydroxybutyrate) (PHB) and poly(hydroxybutyrate) cohydroxyvalerate (PHBv).

c- Polymers chemically synthesized using monomers obtained from agro-resources, for example poly (lactic acid) (PLA).

d- Polymers whose monomers and polymers are both obtained by chemical synthesis from fossil resources, for example polycaprolactones (PCL), polyesteramides (PEA), aliphatic co-polyesters (e.g., PBSA) and aromatic co-polyesters (e.g., PBAT). – From non-renewable resources.

Although all the different categories of polymers can be obtained and experimented with, taking into account the homebased approach for this thesis, it was defined suitable for the following experiments to consider only the polymers coming from a biomass, or agro-polymers. The lasting categories can be considered for future experimentation.

2.3.2 Plasticizer

The council of the IUPAC (International Union of Pure and Applied Chemistry) defined a plasticizer as 'a substance or material incorporated in a material (usually a plastic or elastomer) to increase its flexibility, workability, or distensibility'. Hence, the primary goal of these substances is to improve the flexibility and processability of the polymer it is being mixed with (Vieira, Gurgel, & Altenhofe, 2010).

The Viera, Gurgel and Altenhofe article provides a series of proven biodegradable and edible plasticizers, with different experiments and combinations stating some of their advantages and limitations. This information is useful both to support the future experimentation phase, and as a reference for future biomaterials projects to understand and see additional options of plasticizers to use. Between the list they state the following materials:

Glycerol (GLY), ethylene glycol (EG), diethylene glycol (DEG), triethylene glycol (TEG), tetraethylene glycol and polyethylene glycol (PEG), propylene glycol (PG), sorbitol, mannitol, and xylitol; fatty acids, monosaccharides
(glucose, mannose, fructose, sucrose); ethanolamine (EA); urea; triethanolamine (TEA); vegetable oils; lecithin; waxes; amino acids; surfactants and water as plasticizers of edible and/or biodegradable films.

“Glyecrol and sorbitol are the most studied and used plasticizers” (Vieira, Gurgel, & Altenhofe, 2010).

The article stablishes different benefits and limitation on the use of plasticizers, and suggests concentrations to reach optimal results, summarized in the following table:

BENEFITS	**CONSIDERATIONS***	**LIMITATIONS**
+ Improves molecular chain flexibility + Increase resistance to fracture + Reduce brittleness + Increases film flexibility + Avoid shrinking during handling, drying and storage	• Crystallinity • Optical clarity • Electric conductivity • Fire behavior • Resistance to biodegradation	- Decrease on tensile strength - Hydroscopic (absorb moisture from air – affected by ambient conditions)

Affects depending on polymer base and use

Table 1. Benefits, considerations, and limitations of the use of plasticizers when developing biomaterials.

An additional tool that can be extracted from the article in mention is the effects of the variation on the concentration of the plasticizer in the material mix, being:

USE OF PLASTICIZER

Too little	Too much
• Brittle film • Low elasticity and flexibility	• Exceed compatibility limit with polymer – risk of separation • Decrease of tensile strength • Increase of solubility with water

Table 2. Influence of the use of plasticizer in a polymeric mix.

The point of reference for this table, is between 5% and 10% concentration of plasticizer in the material's mix, a suggester concentration for polysaccharide films (e.g., starch, cellulose, chitin) (Vieira, Gurgel, & Altenhofe, 2010).

2.3.3 Plasticizer

The filler works as a substance to add consistency or structure to the mix of the biomaterial. The filler is commonly used as an enhancer of the material's properties, such as mechanical, increasing its strength, elasticity, or aesthetic, looking to add colors, textures or even aromas. There are no rules on which type of filler or matrix can be used for a biomaterial, and here is where the experimental (and fun) part of working with them start, allowing endless possibilities to profit from an unused material, a material that is considered waste or even a common material that can allow different uses that were not thought of before.

For the experimentation phase on this thesis, by-products such as coffee refute, eggshells, grass, spices, and sawdust will be used due to their ease of obtention, which translates in wide and common use. This will allow us to recognize different possible outcomes for each of them, understanding their way of work and of enhancement of the biomaterial.

2.3.4 Solvent

The solvent is a substance that dissolves a solute in a mix. Usually for biomaterials is water. Tap water is unadvised since its composition can vary along different regions, and it usually gets mixed with additional substances. For manufacturing biomaterials, it is always suggested working with distilled or demineralized water, avoiding undesired and uncontrollable results during the experimentation phase. Even though water's property is to solute, it can also bring benefits or work as a plasticizer, due to its hydroscopic properties, enhancing the plasticization process (Vieira, Gurgel, & Altenhofe, 2010).

Now, depending on the type of mixture that is being attempted to dilute, the solvents can change in complexity, going from vinegar to ionic liquids. In the first case, vinegar can work as a catalyst to improve the gelling process of the polymer, while the ionic liquids work for hydrophobic polymers that aren't able to dissolute in regular solvents. For this research purpose only water and vinegar will be taken into consideration.

2.4. PROCESSES

For this section different approaches to understanding what type of processes have been discussed and explored in the biomaterial's world were taken. First, the literature review considered both experimental and already developed products, where material libraries such as Materiom, DIY-materials, Material District, among others, were used as an initial reference to see what type of products could be done, and the processes, materials and tools that were used. Secondly, getting to know firsthand physical products, designers, engineers, and entrepreneurs that develop biomaterials enriched the research allowing us to understand different perspectives, limitations, tricks, and guidelines on how to work with these. Different expositions from the Design Week 2022 at Milano were visited to understand both the processes and outcome of how the industry and entrepreneurs are approaching their development. The goal of the research was to categorize the different examples of biomaterials products and recipes that were found, considering: shaping, joining and surface treatments.

To develop a tool, is important to understand the already existing options.

What have other people been doing and how have they made products from these biomaterials?

2.4.1 Shaping

Shaping is the initial process in which it is given a form to the material. Industrially, there are already several processes standardized and defined for different types of materials: sand casting, die casting, investment casting for metals, rotational molding, thermoforming for polymers, blow molding for both ceramics and polymers and conventional machining for all the latter, for naming just a few. In this case, since we are developing a new material, certain processes are not defined but mainly made along the way they are being constructed or experimented with. The following exercises allow a way of categorizing similar types of biomaterials on certain ways they are usually manufactured and have a clear understanding on how certain recipes are labored.

2.4.1.1 Molding

Starting from the most essential one it's found molding. Conventional molding is used for many different experiments of biomaterials. Biomaterial mixtures can go from liquid state during its preparation, to high viscosity, to malleable to solid. Many recipes for bioplastics are usually under a liquid state and will need to undergo a drying process to stabilize and dry. These materials are usually verted on containers or molds with different types of shapes, circular, rectangular, triangular, where the liquid will cover the container and therefore, later, the piece will replicate the shape of the mold. These molds or containers are usually made of non-absorbent materials, for example metals, glass, or plastics, so it avoids sucking the water from the mixture, and avoids sticking to the container.

As seen in the following pictures, from designer's workshop of Austeja Platukyte, the students of Vilnius Academy of Arts exposition on Isola Design for the Milano Design Week 2022, interesting material samples created from flower waste, collagen, fillings, and sawdust, allows to understand the molding process they undergo. This molding process just needs pouring and waiting, usually no additional pressure or heat is needed to reach a final sample. Many of the biomaterial's sheets are made in a similar way, where a cast or a big recipient is built, depending on the sheet size required, the mix is then poured and after a drying process a sheet is formed.

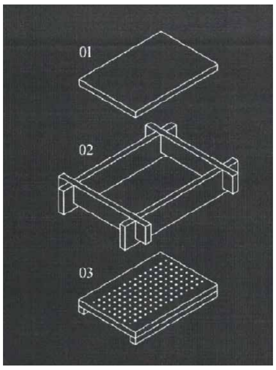
Image 14. Biomaterial moulding samples from the Vilni us Academy of Arts (Vilnius Academy of Arts, 2022)

Advantages: Easy to replicate, easy processability, control on the final shape

Disadvantages: Limits on shapes possibilities, long waiting time to cure (process don't accelerate drying or curing), limits to depth and thickness of the possible shapes to reach due to drying time and mold proliferation

2.4.1.2 Compression Molding

After conventional molding, it is found compression molding step ahead. In this case we have found different samples which approach the use of compression molding to more elaborate pieces, either with structural purpose or to reach a different shape than just a plane sample sheet. The first example analyzed is Post Paper Studio, an initiative that experiments with low tech and do it yourself (DIY) tools to press and generate blocks from recycled paper. The initiative creates a modular mold from recycled plastic of three pieces: a frame to hold the walls of the piece, a base with holes to drain water excess and a moveable cap that allows the compression of the mix. Additionally, Post Paper Studio provides recipes to develop the correct mix to be used with the mold, and the instructions to process it.



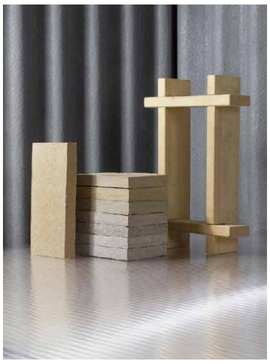


Image 15. Compression moulding machine for manufacturing recycled paper bricks from PostPaperStudio (PostPaperStudio, 2023)

Advantages: Low cost, easy to replicate, control on the final shape

Disadvantages: Limited to certain shapes, limited pressure to apply, requires a machine, tools or mold to develop the final piece.

The last example comes from the Precious Plastics group, a non-profit and open-source initiative from Deutschland that develops tools to produce semi-finished or finished products with recycled plastics. In this case, a department from Precious Plastics calls, Beyond Plastics (BP), develop new tools to provide an alternative to plastics making bowls and cups from heat molded coffee, husk, wheat, and tea leaves. Beyond Plastics, developed a working station with a machine that uses heated compression molding to create solid pieces from these residues. As BP explain, the combination of a closed mold, heat, compression, and a base residue rich on cellulose (e.g., coffee) generates a chemical reaction that allows the water on the base to react with its cellulose creating new and stronger bonds (Precious Plastics, 2020).

Although the machine development is in the line of homebased approach it is very interesting how the exploration of heat and compression, without any additional additive (like plasticizer) is allowed to create a functional, biodegradable, and even compostable product.

Advantages: No need of binders, plasticizer to create the biomaterial, the final piece is sturdy and ready to use, reduces waiting time, control on the final shape

Disadvantages: High cost due to machine building and mold creation.

Image 16. Heat compression moulding machine by Precious Plastics and their project Beyond Plastics (Precious Plastics, 2020)

2.4.1.3 3D Printing

The 3D printing process explores the idea of extrusion of the biomaterial; therefore, a viscous enough mix must be created to flow through a nozzle, be solid enough to sit and dry while pouring, but liquid enough to flow. Polymeric 3D printing already has hundreds of variables to being taken into account, from nozzle size, type of polymer, heat of the nozzle, heat of the plate, and then certain conditions that can be controlled for the type of printing, layer width, layer height, number of outer walls, filling, velocity of printing, and more. All these different attributes define on one side the quality of the print, but also serve to portray the complexity of the process.

Designer Markous Georgiu was able to develop a complete package of extrudable and 3D printed biomaterial, including, first, an extrudable biomaterial made from oyster shells, honey, water, and sodium alginate (Georgiu M. , 2022), that is viscous enough to flow and stick between itself while pouring. Secondly, a DIY -BIOGUN- that allows to make the extrusion. This BIOGUN works while adapting a screwdriver with carefully designed 3D parts to evolve the initial tool to a bio-extruder. With this kit Georgiu is able to create different patterns, extrude in two dimensions creating lines, patterns, or text, and even generate solid 3D extrusions, carefully layering the extruded material. The tool works more as a brush and lacks accuracy due to its human handling method, which with further development can reach to an automated model. Additionally, although the material behaves remarkably, the limiting of the grain size must be taken into consideration since too big grains could clog the nozzle.

Image 17. DIY Biogun made by Markous Georgiu (Georgiu M. , 2022)

Even though the previous example might not enter the category of 3D printer it does explores the idea of extrusion and 3D modelling accurately. On the other hand, currently there are already commercial and industrial 3D printer models that are able to print with different materials than plastic, for examples models as PotterBot, WASP or StoneFlower, allow the 3D printing of clay-like materials. Since these machines handle viscous materials, the extrusion process is quite different as a FDM (fusion deposition modelling) printer, where either by air pressure, mechanical pressure, or an endless screw mechanism the material is expelled through the nozzle.

Some DIY approaches use these same mechanisms to experiment with other materials than clay. For example, the designer Ana Otero, uses an eggshell mix made with water and Xanthan (gelling agent - polysaccharide extracted from the fermentation process of sugar through a bacteria called Xanthomas Campestris (Habibi & Khosravi-Darani, 2017)). The process is open source and can be found in Materiom, where Otero explains the measures, procedure, tips and, very important, printing specifications such as speed, pressure, and layer height (Otero, 2022).

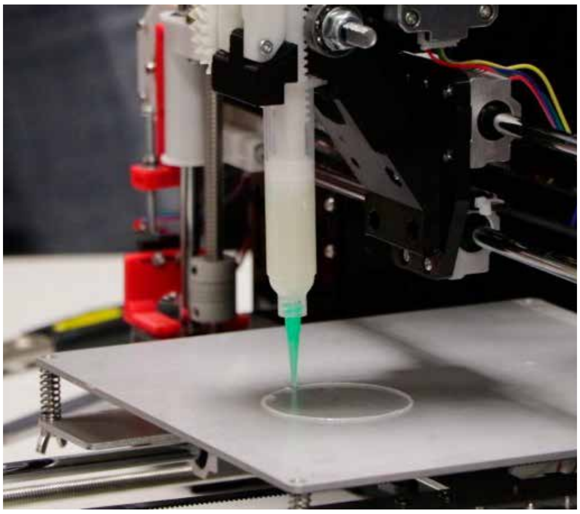


Image 18. Example of 3D printing solutions suited for biomaterials: (1) 3D Hydraulic machine suited for viscous liquids (3D Potter, 2022), (2) Tinkered biomaterial 3D printer (EDDM, 2020), (3) Ana Otero 3D printing biomaterial prototype based out of egg shells, (Otero, 2022)

Advantages: Allows complicated 3D pieces creations, automates the process

Disadvantages: Complicated mixture, small variations on the mix might ruin the piece or not even work on the printer

2.4.1.4 Folding

Although for folding there is usually a previous shaping process, either molding or stamping, the folding processes can give additional volume and shape to the sheet-like biomaterials. There are different projects such as Lugae from Valentina Márquez and Carolina Pacheco from Chile's Fablab (Pacheco & Márquez, 2020) or Unfold from Lionne Van Deursen's studio, that explore the different possibilities of creating relief surfaces or three dimensional pieces, pieces that can move, contract or expand making them more dynamic (Van-Deursen, 2020). Although the first example is a bioplastic made from a mixture of carrageenan spirulina and the second one from bacterial cellulose, both materials are allowed to be treated in a way that resist additional manipulation, such as folding, permitting creating these interesting shapes.

Advantages: Recreates 3D shapes with thin sheets of materials

Disadvantages: Limitations on the type of shapes that can be achieved, and the process can debilitate the material.

Image 19. Examples of biomaterial products made through folding: (1) Karagenina base bioplastic folded prototype (Pacheco & Márquez, 2020) (2-3) Lionne Van-Deursen's UNFOLD project samples composed of bacterial cellulose and finished through folding (Van-Deursen, 2020)

2.4.1.5 Laser cutting

Laser cutting can also enter in the category of secondary shaping processes, where an initial creation, and shaping process must have taken place. When managing sheet-like biomaterial shapes or pieces laser cutting is a fitted process to profit from. In a similar way folding does, laser cutting is allowed to give a different use to the biomaterial, either by developing a pattern for a clothing piece, or a pattern to allow more properties such as elasticity, strength, translucency, porosity and more.

FabTextiles is a fabrication laboratory focused on textile, fashion, and sustainability. They have developed both different recipes and processes to showcase the advantages of laser cutting. The first project is BIO RIOT, a textile made from sodium alginate and coffee waste, made via laser cutting for the outline and laser engraving for the label on the piece. The project was worn for the strike against climate change in Barcelona, in September of 2019 to raise awareness on the topic considering that, fashion industry is one of the most contaminating one in the world, and secondly to raise the voice with different possible alternatives to conventional textiles. With the same recipe, FabTextiles was able to develop a bio-leather bag, approached through a laser cut blueprint. The interesting approach of this bag is that no additional joints are needed for its assembly, the bag can be built by the joints generated from the same laser cut pattern, avoiding both post processing and additional (maybe non-biodegradable) materials.

Image 20. Biomaterials' laser cut examples: (1) Sodium alginate coffee-based crop-top laser cut (2) Sodium alginate and coffee-based purse laser cut (FabTextiles, 2020)

Although laser cutting, both for biomaterials and regular materials, are used mainly for sheet-like materials, two students from the university of California (Lasaro Vasquez & Vega, 2019) tested additive manufacturing techniques, such as laser cutting and milling, for electronic prototypes using blocks of mycelium. In their research, they were able to reproduce working components for micro-electronics, such as breadboards, casings, and bases to embed electronics. They use laser cutting techniques either to carve the appropriate slots for components such as batteries, microcontrollers, LEDs, and cables.

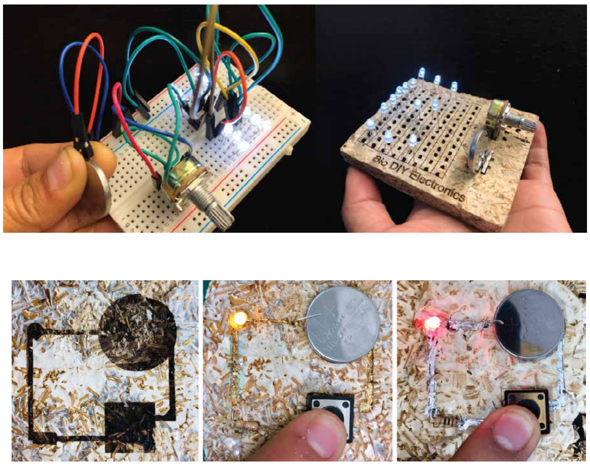


Image 21. Laser cut and engraved mycelium block used as replacement for a protoboard case (Lasaro Vasquez & Vega, 2019)

Advantages: Allows complicated patterns, adds visual value to the piece, allows both branding, cutting, engraving processes.

Disadvantages: Material can be easily damaged if not used accordingly. Needs a lot of experimentation to reach desired result, since working with an equally experimental material.

2.4.1.6 Milling

Unlike laser cutting, milling is rarely used to process sheet-like materials. On the other hand, milling is commonly used as a process to remove material not only on two dimensions, but in a three-dimensional way. The process is allowed to carve the piece by removing material with a certain degree of precision that must be assessed when working the piece, considering its fragility. Recalling one more time the study from Lasaro Vásquez and Vega, they also experiment by milling blocks of mycelium. In their findings, they state how fine engraving processes were difficult to achieve given the roughness of the substrate (hemp) they used for the mycelium, achieving sloppy results, and assessing it more suitable for carving large pieces or removing big amounts of material.

Moving to an industry-based example, it is found Keep-Life a material and product development company that aims to produce goods with an end-cycle life in mind, meaning their products shouldn't go back to being recycled or upcycled but go back to the nature The material that Keep Life uses is generated using the shells of hazelnuts, chestnuts, walnuts, almonds, pistachios and peanuts, with the addition of a binder free of harmful substances, fillers and fillers, of solvents and formaldehyde (Keep Life, 2022).
The material block Keep Life produces is allowed

to being cut with saw, sanded, drilled, and finally milled, a material strong enough to endure quite abrasive processes to undergo several shaping processes. The material on its fabrication process undergoes a compression stage made by hydraulic pressing and a drying stage that lasts from 20 to 30 days. First, the compression process, as seen for the Precious Plastic's process, allows the material to strongly bind, while secondly, the natural drying process avoids the material to have abrupt temperature shifts limiting the apparition of bubbles, holes or cracks that might damage the material. These processes allow the material to obtain its hardness, and later the possibility of it being milled, among other processing techniques.

Image 22. Examples of milled biomaterial blocks made of nutshells, from the design studio Keep Life (Keep Life, 2022).

Advantages: Allows to work pieces in a three-dimensional way, either flattening, engraving, sculping, reaching intricate shapes.

Disadvantages: Due to the naturality of biomaterials, the drilling bit tends to melt the binder making it stick to the same, avoiding a proper cut. The process tends to be aggressive, therefore the material has to be strong, or else it will damage the piece.

2.4.1.7 Sculpting

Another approach to molding can be seen in the Mat-wise project, a project where Industrial and Material Designer, Sofia Perales, experiments the different uses of egg-cement. In this case she uses a mixture of water, gelatin, and shredded eggshells, to create a cement-like material that when hardened takes the appearance of a ceramic. In one particular project she uses inflatable balloons as a mold base, where, by pouring the material on top of it, once hardened, takes the shape of the outer part of the balloon, becoming, as she calls it, a planet (Peráles, 2022).

Due to the characteristics of some biomaterials, sculpting and molding them, such as plaster, can be done. These types of shaping allow much more freedom, but much less accuracy in the final piece. Still, the shaping process allows the designer to experiment and to understand the limits of the material in a more free and creative way.

Advantages: Freedom in manipulating the material, being able to generate intricate shapes. Can be easily and rapidly done

Disadvantages: Lack of accuracy and structure. A sculpted material will usually tend to be used for decorative or artistic products, but not functional ones.

Image 22. Examples of milled biomaterial blocks made of nutshells, from the design studio Keep Life (Keep Life, 2022).

2.4.2 Joining

Materials can undergo an additional process to complete a product in which joining different pieces, either of the same material or elements that give structure or additional functionality to the same, allow the piece to come together. Different joining processes are used on biomaterials to render more complex the product or to reach different functionalities. Also, the jointing processes serve to make use of materials that are already present in nature (that didn't even have to be manufactured) and develop a product from them. The following projects will exemplify some of these examples.

2.4.2.1 Sewing

Sewing is a process usually used for textiles where a thread is intertwined two different pieces to join them. In this case, sewing can also be used for biomaterials, where the sheet samples already seen created either by molding or stamping transform into something bigger. Berlin Artist Bela Rofe exemplifies this in her project Weaving Water, where she uses algae-based bioplastics, human hair, natural dyes, and algae yarn to create a daunting bio-tapestry of 1.35 meter of length and 2.10 meters of height. In this case, Rofe takes one step further the bioplastic sheets making them a complete art piece where she aims to portray how humans and nature should collide into one living entity in the art piece.

Image 24. Weaving Water, tapestry of algae-based bioplastics and human hair by Bela Rofe (Rofe)

In this next example, in her project The Present is a Gift, the Material Designer Quinn Van Etten develops bio-textile art pieces where, by recollecting locally sourced plants and with the use of a domestic knitting machine, she can create a new piece. In this situation there is no need to develop an additional bioplastic or bio-sheet, the use and collection of what she calls vegetal skin, plus a keen eye and amazing crafting skills, are sufficient to develop, in this case, an art piece.

Image 25. Sewn plants and leaves by Quinn Van-Etten (Van-Etten, 2021)

Finally, a similar approach made by the designer Jeannet Leenderste, takes advantage of the surplus of seaweed commonly found on the northern Atlantic Coast, to produce vessels by sewing them with waxed linen. Leenderste not only learned the technique on how to sew the rockweed, but also on how responsibly harvest the materials, with the hand of Rockweed Coalition.

Image 26. Sewn surplus seaweed sculptures by Jeannette Leenderste (Leenderste, 2023)

Advantages: As folding technique, a 3D piece can be produced by, in this case, the union of various pieces. The process is accessible to anyone with string and needle.

Disadvantages: Time consuming. Outcome relies on artist's ability.

2.4.2.2 Joints

Seeing a section of the biomaterials developed as a textile replacement, it is useful to think in all the different ways normal textiles can be joined together to explore different ways of joining and shaping biomaterials. From rivets, buttons, zippers, all are valid options to complement these materials that are being developed to obtain a finished product.

Biomaterials can also be the means or part of a whole to compose or complement a finished product. In this case, designer Benjamin Hubert explores and executes this idea with its modular screen system made of triangular hemp tiles. For this project Hubert designs a modular skeleton in which the triangular hemp tiles, aided by three magnets at their corners, are wrapped, constructing an acoustic division, modular screening product. The interesting thing about this project is how, by the combination of three elements, a base biomaterial sheet and two joints, can already build a system. The modularity of the system also shows the different possibilities of how it can morph into some other product: a chair, a sofa, a roof.

Image 27.Benjamin Hubert modular structure of hemp-based panels (1) Pieces that compose the panel, (2) Mounted panel (Hubert, 2015)

Advantages: The mixing of materials and pieces can generate a more complex and elaborate product. Usually, the structure may not give it the biomaterial but the additional pieces or joints that put together the object. Being biomaterials commonly fragile, it allows to profit other of their properties, such aesthetic, compost ability, texture, without the need of needing the material to being also strong.

Disadvantages: The process adds a different material to the creation of the product, therefore it should be thought further the disassembly and disposal of the same, since now is not only completely biomaterial made.

2.4.3 Surface treatment

The final touches for certain products or material are usually made and defined for aesthetic or protective purposes. In the case of plastics, metals or even natural based products like wood, the finishing treatments commonly render the product with properties such as resistant to water, fire, mold, sun exposure, air, any of these depending on the material's purpose. Although their application enhances the product's performance, it usually comes with an environmental cost. Many of the varnishes, paintings and surface treatments are toxic, extending their biodegradation time or constricting its recycling process.
For biomaterial treatments no product that may harm or make them non-degradable is out of the question. But there are still ways to further protect or enhance aesthetically the product without making it toxic, even developing these treatments from a homebased approach.

2.4.3.1 Dying

Painting and dyes initially came from either animal or vegetable-based extracts. Henna, animal blood, curcuma, are different types of dyes or paintings that have been used for centuries all coming from a natural extraction. For the biomaterial approach Materiom provides several dying recipes in a wide range of colors. There are several methods of pigment extraction but the most common rely on boiling the base which the dye is going to come from, usually around 30 minutes (the more time left, the more the pigment color will intensify), then sieve it several times to remove the lumps from the base, let it dry and then it is ready to use. From cabbage, sage, turmeric, onion skins, dragon fruit, avocado pits, noni fruit, different vegetables, or flowers, the extraction process can be executed for all of them.

Image 28. Purple cabbage dye

Advantages: Provides a different aesthetic to the product, allowing flexibility in the design choices.

Disadvantages: Natural dying, depending on the source, can cause bad smells or even mold if not well treated.

Advantages: Provides a natural and protective finish to the product, prolonging its usable life, if so is required.

Disadvantages: The mixture of natural varnishes can be difficult to integrate in a biomaterial product since the polymerization process may avoid the impregnation of the same.

2.4.3.2 Varnishing

Varnishing processes are usually applied to provide protection for the material, providing and enhancing its properties. Now, going to the word's root a varnish is "a liquid that is painted onto wood or paintings to protect the surface, or the hard shiny surface it produces when it dries". There are different types of natural varnishes that nature itself provides, such as amber, honey, wax that provide a certain degree of protection to the final material. Is important to notice that, since the varnish objective is either to improve aesthetically or prolong products' life, it should be discussed to what extent it should be used on a biomaterial. The use of varnishes on biomaterials might close the gap between their properties and industry demands but will be limiting on their compost ability and biodegradability. Until now, not many studies have been made on biomaterial varnishing, and starting from wood references, and experimenting with the ones already in the market should be an objective for future research.

CHAPTER
THREE

Circular economy and circular design

The circular economy mottos: eliminating waste and pollution, circulating products and materials, and the regeneration of nature.

This research thesis aims to explore the conditions the biomaterials support to the inclusion and development of circularity in the economy. Additionally, it approaches different guidelines needed to be taken into consideration during the development of -any- product (bio based or not) considering, stating, and analyzing principles of Circular Design and Design for Sustainability (DfX).

As stated in the introduction of this research work, the economic models adopted in the early stage of industrialization have caused grave harm to the planet's environment. From this, different strategies have appeared trying to mitigate the damage linear models of productions have caused to the planet. For example, generating eco-friendly initiatives, planting more trees, developing 'greener' products, to the famous 4 R's of reduce, reuse, recycle and recover. All these concepts have been evolving and have been consolidated to being now enclosed in different aspects of Circular Economy.

From the article A conceptual framework for Circular Design (Morelo, De los Rios, Rowe, & Charnley, 2016) the authors define a well stablished categorization (taxonomy) for different economies of scale (or business models) that are enclosed in a circular economy. These categories will be useful to later connect and exemplify different product (some biomaterial-based) business that can be characterized with one or more of these.

Taxonomy of circular economy is simplified in 5 categories: Design for circular supplies, Design for resource conservation, Design for multiple cycles, Design for long life use of products, Design for system change.

The following section will be describing and showcasing different examples of the taxonomy of circular economic models which will aid for the latter development and production process, for both the tool and for the final product made out of the biomaterial.

3.1 DESIGN FOR CIRCULAR SUPPLIES

As one of the first models explained in the article, the Design for Circular supplies, is probably the one that defines what the aim of biomaterials, and bio-products try to achieve with their development. In this case, referring to products that after their use, can be disposed of and will either aid or not damage nature. In many cases, this means that the disposal should be compostable or biodegradable.

Understanding this process is critical for the creation process since it allows the designer to understand the reach and limitations of the product being developed. For this case, if a product has to be disposed of and compost, its properties have to be in line with these characteristics. For example, materials that need to resist abrasion, acidity, light exposure for long periods of time, like construction materials, might not be suited for this model of circular design. On the other hand, one time use products, such as cups, napkins, wrapping films and so on, can. Going back to Precious Plastic's project, Beyond plastics, the example of a Circular Supply design is perfectly showcased. A cup or a bowl hot pressed, made from organic waste, such as tea leaves or coffee waste, that after its use can be disposed of as organic waste and after a few days will start decomposing. This example can be used as a homemade or semi-industrial approach, where the production of such a product can be limited by the possibility of a user to build the hot press.

A different example in Italy that have gone beyond the semi-industrial or DIY ambit to produce products or materials that comply with this model of circular economy is Aboca, a healthcare company that focuses on producing health and wellbeing products from medicinal herbs. Defining their vision from the idea of curing the body from nature-based products, that eventually will return to nature when already used, Aboca has become leader in the healthcare sector, with over 40 years of trajectory in the market. As the company states, they go beyond the circularity the products portray, but by training health professionals, generate awareness on the importance of connection to the surroundings and how the natural products can be beneficial and helpful for our body (Aboca, 2022).

Image 30. Adiprox, metabolism natural tea capsule (Aboca, 2022).

Bio-on is another Italian company that through research and development, aiming to reach a circular supply economy, developed a plastic called Polyhydroxyalkanoato or PHAs. A material produced from the by-product of sugar that is able to decompose on natural base water, such as rivers or seas. A completely revolutionary material that tackles the problem of water or rivers contaminated by microplastics. As the company states, the product biodegrades in bacteriologically non-pure water, meaning that in regular water streams the plastic will be able to dissolve even in the short period of 10 days (bio-on, 2022). Even though the products showcased are highly technical, the responsibility of product developers lies in knowing, replicating and analyzing their extent.

3.2 DESIGN FOR RESOURCE CONSERVATION

Design for resource conservation talks about a design approach where products are thought and projected with the minimum resources in mind. This statement can go for the product itself but can also relate to its production process . Starting with the product itself, Design for Resource Conservation can be directed to the different materials used for a certain product's production. When thinking about a wooden table, usually it will not be only made of its wooden pieces, but will include glue, screws, bolts, rods, and maybe for its finishing glass, plastic caps on

Image 31. FUTURECRAFTLOOP, totally recyclable running shoe

its legs to avoid scratching the floor, and so on. An assembly of a product like this, even though sturdy, will complicate its disposal at the end of its lifetime thanks to the different types of materials present in it.

This strategy of sustainable design aims for a design where the minimum possible resources, materials in this case, are used to produce a product. When thinking about the specific example of the table, a way to reduce the number of pieces can be aiming at the joinery, meaning avoiding bolts, rivets, screws and nails.
Adidas is one of the companies that has taken this argument to develop and drive its products. In 2019 the company was able to produce a 100% recyclable performance running shoe called FUTURECRAFT.LOOP. Due to the complex material mixes, and the glued components,

shoes can only be downcycled or not recycled at all. The company approached this issue by using only one material for the shoe fabrication (Recycled TPU), and no glue for its assembly. Once the shoes have completed their life cycle they are taken back to Adidas, where the shoes are washed, shredded into plastic pellets and then melted in raw material that can be used for a new pair of shoes (Adidas, 2019).

3.3 DESIGN FOR MULTIPLE CYCLES

shoes can only be downcycled or not recycled at all. The company approached this issue by using only one material for the shoe fabrication (Recycled TPU), and no glue for its assembly. Once the shoes have completed their life cycle they are taken back to Adidas, where the shoes are washed, shredded into plastic pellets and then melted in raw material that can be used for a new pair of shoes (Adidas, 2019).

The role of this strategy during the design process is to understand the extents of the materials of the product during its life cycle. The definition of the disposal, recycling, upcycling, re-use of the product's materials can be guided through the different cascading paths the materials that compose the product have (this process will be useful to understand the latter selection of the biomaterial's base.).

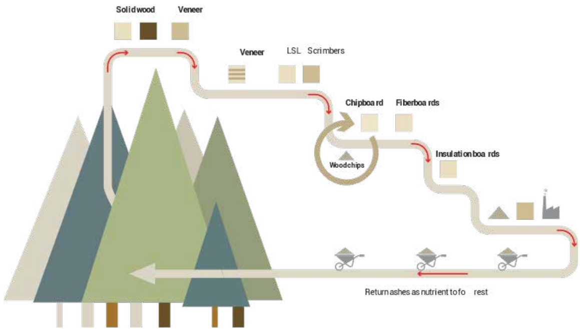


Image 32. Wood cascade according to cradle to cradle (Ellen McArthur Foundation, 2014)

3.4 DESIGN FOR LONG LIFE USE OF PRODUCTS

As talked previously, programmed obsolescence is one of the main contamination issues in the product world, a practice led by the sole purpose of companies to sell more. Good quality products will last for very long years, but for the companies that means that the re-purchase time will be further apart. Design for long life use of products aims to extend products' life either by offering a maintenance system, by enhancing the product itself or establish longer relationships between user and product.

A market where programmed obsolescence can be clearly seen is in the technological one. Cell-

There are other ways in which the longevity of a product can be distributed and prolonged, tackling, for example, the ownership of the same. Sharing and swapping systems allow products to have a life extension further than it could have with only a single user.

phones, computers, tablets, all of these appliances advance at such a speed that the re-purchase of the products is not made because the previous one has been damaged, but because a newer version has appeared. In a world where new is better, avoiding the craving for a new device will hardly be an option, but there are companies that see it differently. This is the case of Fairphone, a smartphone company that focuses on producing responsible products, considering its user, its market and, very importantly, the environment. They tackled the planned obsolescence by developing a phone that is thought to be repaired, reused and recycled. They produce a modular cellphone that can be easily opened and accessed, contrary to their competitors, and either repair or replace just the piece that's broken, without the need to buy a whole new device.

Image 33.Modularity of Fairphone cellphone showcased with different of its parts which can be taken out and replaced if damaged (fairphone, 2022)

The way the business model is thought of works towards sustainability in the sense that allows the product to last longer, not just because the user wants to, but because the same company facilitates it.

3.5 DESIGN FOR SYSTEM CHANGE

The previous example allows to introduce to the last circular economy strategy called Design for

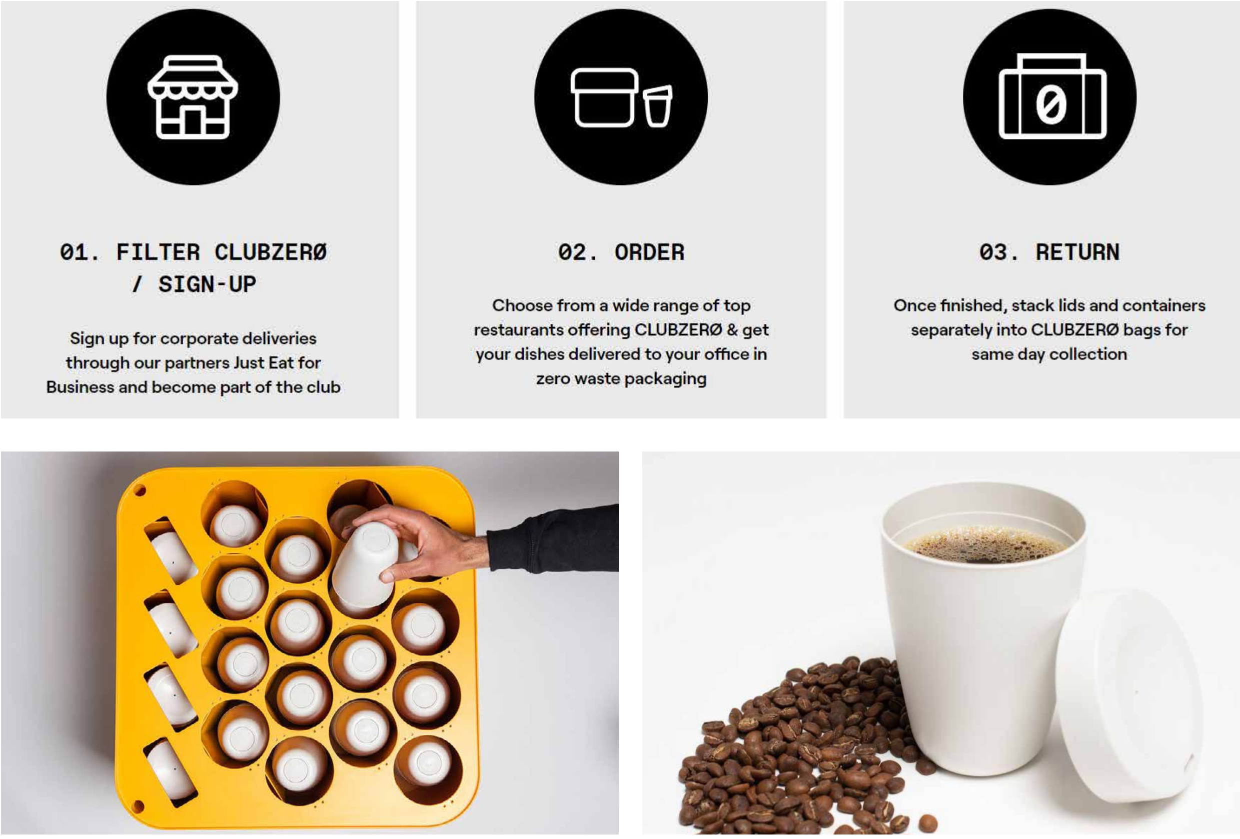


Image 34. (1) Clubzero business model, (2) Clubzero's return case for the used cups. (3) Brand new cup designed for borrowing system (Clubzero, 2022)

system change. As the same name states it, this strategy boards not only the product or the process itself, but the complete system in which the product will be interacting, from the material obtention to the production process, transportation, product interaction, repairing, disposal, recycling and so on. As is seen with Fairphone, they are a company that goes beyond the product to address the need of the user prior and post-sale, considering the market they are in, providing a system that closes the gap between the disposal of a product and its seller.

An additional example that can exemplify this circular economy strategy is Zerocup (previously Cupclub), a company that focuses on returnable packaging (initially for coffee) in retail stores around Europe and North America. The company has designed a series of cups and containers to carry different types of foods, from coffee to salads, that people can take away and when used can be returned at a certain delivery point. In this case, Zerocup is not only designing the packaging but is providing a service to retailers in order to replace one use packaging, considering the pickup, washing and stocking of the containers, so stores and users can request them without polluting with one-use packaging (Clubzero, 2022).

CHAPTER
FOUR

Do It Yourself (DIY)

4.1 WHAT IS DIY?

The term Do It Yourself (DIY) is born as a response to different social, economic and historical factors. The connotation of the term is generally rooted to the 1950's 1960, a post war era where in the United States, Europe and countries hit by it are coming out from an economic recession. Households are looking to cut expenses and labor hand was out of question (Science Museum, 2020). This started pushing a culture where things had to be done in-house, and the familiar nucleus be self-sufficient. Carpentry, plumbery, soldering, electronics, interior decoration, things that involve the maintenance of a house became basic necessities.

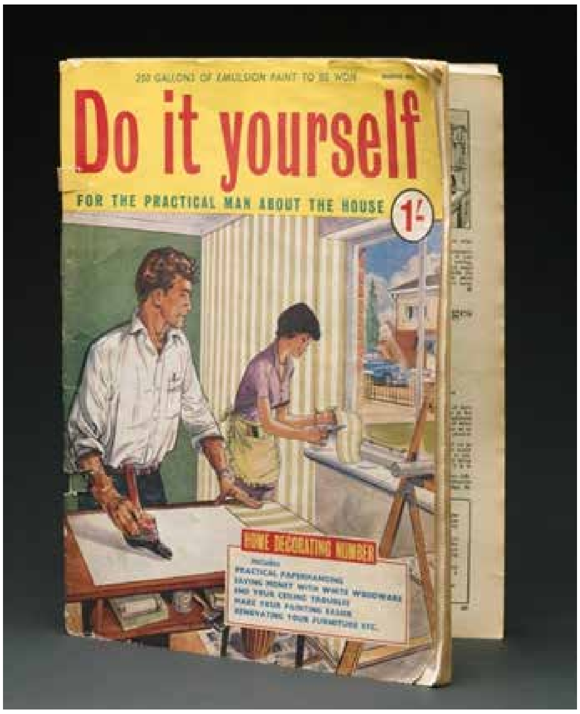


Image 35. Do It Yourself magazine (Science Museum, 2020)

As a response to this need different magazines started responding by including sections of instructible, guides on how to make certain kinds of reparations or decorations to the house. Later a magazine called Do It Yourself was dedicated to a list and guides of projects for people to make in-house. At the beginning it started with simple fixings, like shelves, tapestry, tables, but then, as the demand for this type of content grew, more complex topics started having their own DIY glossary.

To this day, and now with the internet, the Do-it-Yourself concept has been evolving and mixing with new technologies in hand. Now the need is not the same as it was in the 50's or 60's, but it answers, once again, to similar, but at the same time, updated socio-economic factors.

The democratization of knowledge and information through the internet is one of them. Now, there is not just one or two entities in charge of communicating knowledge and DIY projects, but it is the same users that through tinkering and experimentations (and thanks to the internet) share their guides and ways of doing, hacking and solving things. Platforms such as Instructables, Thingiverse, or Make, are community made sites where people can share their projects, allowing them to receive feedback from a specialized community, but also share the knowledge with others.

DIY has become the modern craftmanship

4.2 MAKERS AND MAKERSPACE

As stated by authors Neil, Alan and Joen-Cutcher Gershenfeld in their book Designing Reality: How to Survive and Thrive in the Third Digital Revolution, there have been different digital revolutions where the first two, promoted by the birth of internet itself, transfer the value of materiality to knowledge, meaning a growing importance on disseminating intellectual over manual work. Whereas the third digital revolution gives a turn back to manual work, where the knowledge itself allows us to modify the physical world through digital interfaces, bits can modify atoms as they call it. This way of producing physical objects, through digitally aided equipment adopted the name of digital fabrication.

Tools usually connected to digital fabrication are 3D printers, CNC (Computerized Numerical Control) milling machines, and laser cutters. These types of machines make a big leap from what usually people have at home and a DIYer (person who develops DIY projects) can make. Initially these where incredibly expensive machines were only big companies had the chance to purchase, but the evolution of technology has allowed the democratization of these tools, providing smaller, cheaper and more home friendly models. Now, the possibilities of creating with these tools are almost endless, same as the different DIY guides that can be found for each of them. This technology-based extension of DIY has been called 'maker culture'.

Image 36. (1) First 2 axis moving optics CO 2 laser cutting machine (1975) Photo courtesy of Laser - Work AG (twi-global, 2002) (2) Flux beamo mini laser cuter for desktop (Flux3DP, 2023)

The maker culture had grown not solely due to the democratization of technology but also addresses the possibility and freedom of not depending on a third party to solve an issue, to a sense of accomplishment of being self-sufficient, but also on the crafting and personalization it allows. Prof. Lucia Rampino, states in her book Evolving Perspectives in Product Design, a beautiful way of stating how digital fabrication reinforces a profound human desire to make things (Rampino, 2018).

Image 37. Opendot Fablab. (1) CNC and woodworking station (2) 3D Printing station

From the maker culture, and hence community, certain spaces designated to aid and gather makers have been showing up more and more. It is true that prices of machines have been going down, but again, sometimes, dimensions, power and capacity (and budget!) for home machines can end up short for the requirements of many makers. These designated spaces aid on this necessity providing a spot where makers can borrow, use and learn how to use the machines. These places can be called creative workshops, maker spaces or fabrication laboratories, most known as Fablabs. Other than lending the machines these places are based on the foundation of democratizing knowledge, therefore promoting learning courses, activities, seminars, all based on a DIY philosophy.

4.3 A SUSTAINABILITY MINDSET

Now the search for being a self-producer correlates with the idea of sustainability, and how you can produce and consume just what you need. It is not in vain that the maker community, the DIY culture and the Fablabs, most of their projects (if not all) relate with sustainability concepts such as recyclability, up-cyclability, reusing, fixing, hacking, recouping and circularity (within all the aspects already mentioned). As Rampino states, being a maker is not just simply possessing good manual skills and technical knowledge used to manufacture objects, but to have a critical thinking towards consumption and production (Rampino, 2018).

Although the goal of being completely sustainable or detaching from industrial models is far from realistic, the DIY culture tries going every step a little further on how and what can be self-produced, self-developed, self-made. Biomaterials, or biodesign enters as a subject to fill the gap of the building blocks with which the products are being made. DIY biomaterials are born from the same DIY bases though at a different level, and with a different medium in mind: instead of creating your own product, you are creating your own material. As seen in the previous discussion, DIY comes to interest of this research project because is the base of experimentation. The beauty behind biomaterials, as the foundation of DIY, relies on the democratization of knowledge, in this case democratization of life sciences and biotechnology (Rognoli, Alessandrini, & Pollini, 2021). Now, it is intended that the project take a further step, not only considering how DIY interacts with biomaterials but how, through digital fabrication tools and makerspaces, the process of biodesign can be clearly enhanced.

CHAPTER
FIVE

Sawdust

The following analysis of circularity for the sawdust is done based on the material selection referenced and supported in the following chapter of this thesis: *Chapter 7: Procedure and analysis*. For this research project, an analysis, and experimentation of different by-products useful for the biomaterials recipes was done in order to understand their feasibility of manufacturability and processability, considering their way of obtention and disposal. The following section will analyze some of the aspects that involve the generation, the treatment, limitations, current and possible uses of sawdust as a by-product.

5.1 GENERATION – OBTENTION

Wood has become one of the most used renewable resources all over the world, counting that forests cover around one-third of the earth's total area, meaning around 1.0 trillion m3 of total tree biomass, where 1,9 thousand million m3 is harvested a year. The material itself is priced for its versatility where, from this total production quantity, the majority of it (27% of global production quantity 2020) is used for fuel, hence energy generation. Other major uses for the material go to sawlogs and veneer logs (mainly used for construction – 16%) pulpwood (used for paper manufacturing – 9%), sawn wood (for furniture and construction – 7%) and chemical wood pulp (to produce polymeric derivates such as methylcellulose – 4%) (Food and Agriculture Organization of the United Nations (FAO), 2020).

Thanks to the versatility and currently increasing demand of the wood, it is forecasted that by 2030 the production of wood will be insufficient to supply its demand in Europe. Because of this, analyzing different circular strategies to render more sustainable its production, either by prolonging its lifespan and/or re-process its by-products, becomes even more necessary (Besserer, Torilo, Girods, Rogaume, & Brosse, 2021).

Sawdust is a by-product born from wood, generated through its manufacturing and transformation processes such as milling, sawing, sanding, planning, routing. The laboring of the material shatters lignified wood cells generating whole cells or group of cells, called sawdust and chips, respectively. The more cell shattering that occurs, the finer the dust particles that will be produced, meaning that processes like sawing or milling will be prone to produce a mixture of both whole cells and cell groups (chips and dust) while a sanding process, due to the fine and constant material removal that the process accomplishes, will be generating finer dust particles (World Health Organization, 1994).
Depending on the type of work being done there are different processes and machinery to gather the material: from simple manual dust sweeping, to more sophisticated vacuum dust collectors. Sawdust is mainly

produced in workshops, woodworking shops, timber factories, fabrication laboratories, and similar places where these types of machineries are used, related mainly to the furniture and construction industries (World Health Organization, 1994). The recollection method will be similar according to these environments but will vary on size, quality and quantity of material that each can process. For example, in a personal workshop there probably won't be a vacuum filter for the dust, but maybe a regular vacuum cleaner, or even just a broom and a dustpan.

5.2 TREATMENT – LIMITATIONS

Although raw wood waste, like saw dust, is commonly used to produce new materials, such as particleboards (MDF, OSB, plywood and such), the end life and recycling part of this semi-fabricated products is far more complicated than its initial steps due to the presence of glues, additives, and formaldehydes initially used to produce them. As seen in the previous section, in this case, the Design for Multiple Cycles is broken, where the recycling of the material after its use is limited by its components. The wood used in particleboards cannot be used later in the regular cascading process that it initiated.

As seen in the studies of (Henrich Lubke, 2020), the recycling deterioration of particle boards, into producing new ones is determinant, and can hold until a limited quantity of reprocessing. This means that, at a certain point, the recycled particle board will not be suited for its initially required applications and will have to be disposed of. As stated from Henrich Lubke, "Low-cost paper liner could be a solution for the final stages of cascading of glued wood-based composites, but wider research is needed." (Henrich Lubke, 2020). With this quotation, Lubke gives the idea on how a certain line of products (for him a low-cost paper line), can be developed from this dying particle board. The idea of using the sawdust (or even the dying particleboard itself) to create a new material, and eventually a new product, not only allows to prolong the lifespan of the material opening a branch in its cascading cycle but stimulates the interest of using the current waste generated by them.

The use of natural additives both to create non contaminating wood-derived products makes this research necessary to contribute to an upcoming increased use of this material.

5.3 ADVANTAGES - USES

The use of the sawdust depends on the context in which it is being generated and obtained. As a practical matter, in this paper two different contexts will be taken into account, one where sawdust is produced in big quantities, and one where is produced in small ones, one being a sawmill and the other one a workshop, respectively.
Sawmills are locations with powered-driven machines, specialized on sawing logs into smaller, usually rectangular boards or beams (Britannica, 2023). These locations make part of the initial step on the value chain where wood starts being processed and transformed. Due to their naturality these locations produce immense quantities of sawdust, which they sell or use as a font of energy for their machines (Cnafield, 2008) (Hurtes, 2022). - Actually, nearly half of the woody biomass is used to produce energy (European Comission, 2019) -. When sold, the sawdust can go to farmers, as a source of fertilizer or animal bedding, to companies that manufacture particle boards, and/or to manufacturing plants, that use the product directly as a source of energy (usually through an intermediate step where the sawdust is converted into wooden pellets (Kofman, 2007)).

Woodworking shops on the other hand, make use of the product generated from the sawmills, and their generation of sawdust is considerably much lower. For this research process an interview to ten different people which have had experience working with wood, either have had their own woodworking shop, are professional carpenters, or just hobbyist was developed to understand better the use of sawdust inside this context, its manipulation and the perceptions the people have regarding this material.

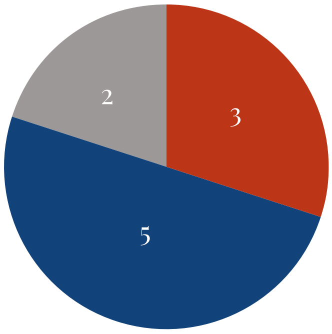
Of the people interviewed, three were professional carpenters, five hobbyists and two just had worked in past times with wood. For this group of people, they produced around 1 to 2 kg of sawdust in a labor day, which doesn't reach near the ton that can be produced in a day a sawmill. This allows us to segment the group of study and have a range in which to focus.

The way they collected the sawdust confirms what was already stated at the beginning of this chapter, mainly by hand or with the aid of a vacuum cleaner are one of the ways most used, but the most repeated way of doing it was with a broom.

As seen in the answers, one of the most used woods is prefabricated or particleboards, meaning the sawdust collected is not pure wood. This

What relationship do you have with wood?

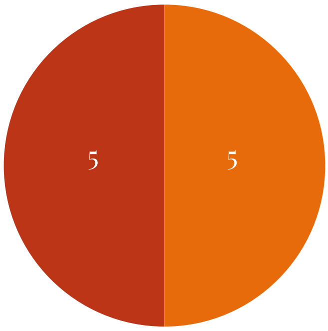
- I am a professional carpenter (I own or work full time in a workshop)
- I am carpenter but practice sporadically
- I am hobbyist, I like to woodworking projects in my free time
- Other



Graph 1. Distribution of expertise related to woodworking experience.

How much sawdust do you generate in a working day?

- Less than 1 kg
- 1-2 kg
- 3-5 kg
- 5-20 kg
- More than 20 kg



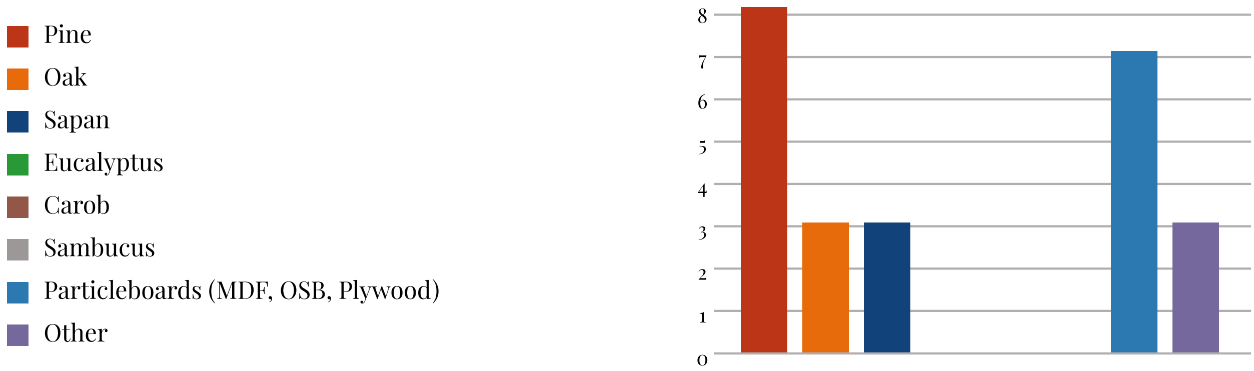
Graph 2. Average quantity of sawdust collected in a day.

With which method do you usually collect the sawdust?

Graph 3. Word distribution regarding most used method of recollection of sawdust.

sets a scenario where in most cases the sawdust collected in this type of workshop cannot be compostable, but either way can be recyclable, different from the one produced on the sawmill.

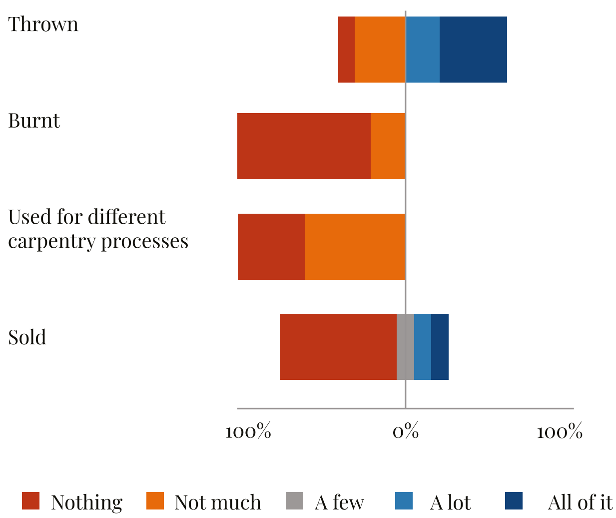
Which type of woods do you work?



Graph 4. Distribution of commonly used type of woods.

Finally, one of the most interesting pieces of information gathered from the survey was how the woodworkers used the obtained sawdust. It was asked in what proportion they either threw it away, burnt it, reused it (either to dry wood, fill holes, cleaning, making other products), or sold. At this point, the majority of the interviewed people confirmed that the totality of the sawdust they used was thrown away. Daniel Mora, one of the interviewed carpenters stated that previously the sawdust could be sold more easily (or even given away instead of throwing it), either for cat litter or as fertilizer, but now, due to 1) hygiene issues, and 2) the mixing of regular sawdust with particleboard sawdust being more and more common its sale has been tightened and limited. It is interesting to see how, although there are lots of different practices and uses for sawdust inside a workshop, they are not as commonly used. This can be due to two different factors: the first one, the unawareness of their uses in the shop, and a second one, which is the most common, that the amounts of sawdust needed is much smaller in proportion to the amount it is produced. In this case, even if the carpenters or woodworkers use part of the sawdust generated inside their woodworking process, the quantity required will hardly ever be greater than the amount produced. This, yet again, confirms an opportunity to reuse and upcycle the by-product in study.

How do you normally handle the sawdust obtained? (Place an estimate)



Graph 5. Distribution of treatment given to sawdust once collected.

This being said there are two problematics that can be confirmed, and which later will be assessed:
The first problematic seen is that the generation of particle boards break the cascading and recyclability features of regular wood, by mixing sawdust with chemicals that later can only be recycled between themselves.

The second is that, for small woodworking shops, the majority of the sawdust generated is being thrown away and wasted, either because there is no use on the workshop, or because it has no demand in its surrounding market.
Through the use of biomaterials, the following research process seeks to give solutions to the problematics exposed.

CHAPTER
SIX

Research design

This chapter will outline the design and methodology of the research: Meaning insights from research, concept definition, prototyping (re-prototyping) and final product.

To understand how to develop a product out of a biomaterial through homemade tools it was necessary to initially understand how biomaterials work: which proven recipes exist? what tools are already used? and what design and manufacturing considerations and limitations they have? Since one of the objectives of this thesis is to develop a semi-finished or finished product, then a usable material must be developed beforehand.

6.1 METHODOLOGY AND RESEARCH DESIGN

Starting with the experimental research of biomaterials it was understood that even though their base of preparation is similar (Polymer + Plasticizer + Matrix + Solvent) almost infinite combinations and solutions of these mixtures could be made. To start constraining the experimental phase it was decided to keep the solvents and the plasticizer fixed, one being water as the main solvent, and the second being vegetal glycerin/glycerol one of the most studied and used plasticizer for biomaterials (Vieira, Gurgel, & Altenhofe, 2010).

For the polymeric bases a list of different ingredients was chosen, both from animal and vegetal origin, being gelatin, sodium alginate, corn starch, agar-agar, methylcellulose and carboxymethylcellulose. The criteria of selection for these polymers were mainly the ease of obtention, the presence of them in already proven recipes, and to have an example of each of the main agro-polymers' groups: *polysaccharides* like starches, cellulosic products and gums, and *animal-based* protein and lipids like gelatin.

Finally, for the fillers a similar criterion for their selection was maintained, ease of collection, abundance and processability. Additional catalyzers such as vinegar were used to accelerate the process of gelatinization of the mixture.
The following table summarizes the selection of ingredients for the experimentation phase.

Base	Name	Origin
Polymer	Gelatin	Animal (Collagen)
	Sodium Alginate	Vegetal (Brown algae (Y.Zhang, 2011)
	Corn-starch	Vegetal Corn kernels
	Agar-Agar	Vegetal (Red algae)
	Methylcellulose	Vegetal (Wood cellulose (Kääriäinen, Tervinen, Vuorinen, & Riutta, 2020))
	Carboxymethyl cellulose	Vegetal (Wood cellulose) (Kääriäinen, Tervinen, Vuorinen, & Riutta, 2020))
Plasticizer	Glycerol (GLY)	Vegetal (Coconut, palm, or soy oils)
Filler	Eggshell	Animal
	Coffee	Vegetal
	Sawdust	
	Grass	
Solvent	Water	Mineral-Natural
	Vinegar (Catalyzer)	

Table 3. Taxonomy - Ingredients on experimentation phase

Continuing, for the research and design processes four stages were defined to arrive at a final development of the biomaterial-based product. The first two stages consider the experimentation the manufacturing of biomaterial sample (starting with basic recipes, and then adding fillers), following a tooling and process prototyping stage, that will consolidate the guidelines for the tool development, and finally the product development phase. In the following section a more detailed description of the stages will be exposed:

Biomaterials basics

For the first stage of prototyping proven basic recipes were taken to the test. Different samples for each recipe were made and, if promising results were shown, the recipe will be screened to follow a second prototyping phase. The recipes, as already stated, were kept in their most basic form (no added matrix) to understand their standard behavior and to have a base point to then understand if additional processing, like adding fillers, molding, or heating, was allowed and if so, how it can affect the material.

Biomaterials and its matrix

Once different basic recipes were tested, different fillers were taken into the mix to analyze their behavior: how does the recipe change, what new variables are encountered during the recipe. Finally, screen and select a filler considering not only its behavior on the experiments, but its sustainability and circularity aspects.

Process and tooling prototyping

Once a sample was defined different shaping of the products were tested through different manufacturing processes like extrusion, conventional molding, compression molding, and sculpting. In this step, different approaches for the same manufacturing process were tested to optimize the final result.

Tool development

Once a recipe, a filler and a process have been defined, a development of a tool that can aid this process was developed. The different insights, references and learnings from the previous experiments are taken into account to develop and provide a set of guidelines that will accompany the tool for it to be used.

Product development

For the product development, the use of the previous four steps is taken into account to develop a usable product through the machinery/processes developed, and the material selected. For this part, an analysis of the material generated has to be done in order to understand its properties, ways of use, limitations and possible outcomes for the product developed.

6.2 INSTRUMENTS

The instruments used during the experimentation phase were ideally of easy accessibility to a semi-professional, artisan, and designer audience, so users with these characteristics can replicate, improve, and profit from the information in this document. The following list is divided in Personal Protection Equipment (PPE – safety first), Production tools, Quality tools, Post processing tools and Other tools used on the experimentation phases.

PPE

Although all the materials and ingredients involved when working with biomaterials are commonly natural, non-toxic, and safe, there are still some precautions to take both for the safety of the user and for the success of the recipe-

- Gloves – Biomaterials recipes can often be messy, having a good pair of clean gloves can be useful to handle better the recipe. Additionally, to avoid any mold proliferation, manipulating the materials with washed hands and clean gloves is paramount.

- Robe: Once again, working with biomaterials can be messy. To avoid getting your clothes dirty (and having also somewhere safe to clean your hands while experimenting) can be quite handy.

Production tools

Many of the production tools needed will be available in a well-equipped kitchen, but although, once again, many of the elements that are going to be used for the biomaterial production are natural, it is highly suggested to use a different set.

- Pot – Pan: Depending on the amount of material to be made the size of the pot should vary. For the initial stage, since experimentation can be done with small quantities, a small pot can be sufficient ~500 ml - 1000 ml.

- Stove: Some recipes will need heating of the materials at some point to react (e.g., for the starch to react with water it requires to be heated so the glucose molecules on it can break down to later generate the gelatinization process (Scientific American, 2012)).

- Molds: As an initial experimentation state any silicone mold can do. The ones used for ice, cookies or cupcakes will work. In this case the idea is to understand the behavior of the material when molded. After some experimentation, more complex molds can be made, either of clay, 3D printed, wax and more. For this thesis experimentation phase silicone molds, clay molds, laser cut Plexiglas molds, 3D printed molds, and wooden milled molds were used to develop sample pieces and final products.

- Blender – Food processor - Mortar: A

tool suitable to shred the materials is useful. Usually, the material that will be shredded would be the filler, e.g., the orange peel once dried, can be shredded into fine orange dust to be combined with the base. The amount on shredding on the filler will vary the forward manipulation with the material, depending on the properties required, bigger fibers can be better for bigger pieces and compression molding, while smaller pieces can be suited either to give just an aesthetic appeal to the mix or to being used for an extrusion process.

- Sieves: In a similar way in which the blender of the food processor was explained, the sieves are useful to be more precise on the particle it is being obtained. Sieves can be found with different grain sizes, and once again the grain size will depend on the properties the user will want to give to the piece.

- Syringe: For the extrusion process syringes of different sizes can be used. The size will always depend on the grain size and on the required thickness of the extrusion. In this case the bigger the grain of the mixture, the bigger the nozzle the syringe should have.

- Rag: Other than cleaning a rag can be a useful tool to extract water excess in the mixture. A microfiber is suggested so when wrapping and squeezing the mix, only water exits and not the mixture itself.

- Clamps: Some of the more sophisticated molds might need additional pressure to set the mixture or to have a better-defined piece – More information regarding clamping and pressure molding will be approached in the following chapter.
- Stirring spoons, pallets, mixers: Due to the viscosity of some mixes, it is suggested using silicone utensils for easier handling.

Quality tools

Measuring scale: A regular food scale can be enough, but a precision scale will always give more control on the amounts and will provide ease of mind to how exact the user is being with the measurement.

Measuring cups/spoons: Even though many recipes will always be in grams, it can come handy measuring cups or spoons to avoid additional steps of units' conversions.

Thermometer: Many recipes will need cooking and heating up, and some of the materials will require certain temperature limits, for example for dying extraction processes some delicate flowers can't go over 80°C (Kääriäinen, Tervinen, Vuorinen, & Riutta, 2020), for other recipes it is needed to check the boiling point for certain materials so they can react.

Post processing tools

Oven: Used for drying processes.

Food dryer: Better than an oven is to have a food dryer. The difference is that, more than heating, the food dryers are designed to pull out the water of the mixture reaching to a better, more controlled and in some cases faster drying.

Other tools used in experimentation

Vacuum pump: The vacuum pump was used to experiment to extract water from certain mixes, to take out bubbles and speed curing and drying process both for mixtures for biomaterials and for molds.

Wax: Blocks of wax were used to carve blueprints for molds that were used to shape and test biomaterials.

Clay: Molds of clay were made to replicate shapes from the blueprints of wax. Clay, once dried, can be placed in the oven without the risk of deforming or damaging. If needed, a mixture can be poured in the clay mold and be placed in the oven for a long period of time allowing to 'cook' the mixture.

3D Printer: 3D Printing machines were useful to print more complex shaped molds, allowing to have 2- or 3-piece molds.

PVC and Aluminum tubes: Used to experiment extrusion processes to reach a bigger semi-finished biomaterial piece.

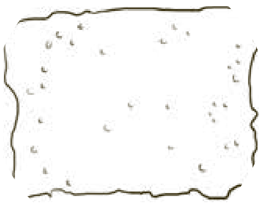
CNC Milling machine: The CNC machine was used to carve blueprints for some base molds, and to develop the final prototyping tool.

CHAPTER
SEVEN

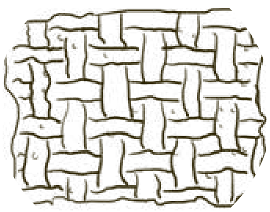
Procedure and analysys

The following chapter will outline the procedure for the development of the samples, experiments, tools, and products during the time of development of the thesis, all while analyzing the different outcomes, referencing relevant literature supporting the results observed.

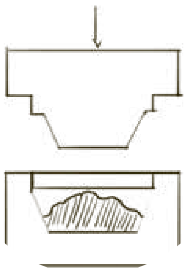
Here the outline of the procedure followed:



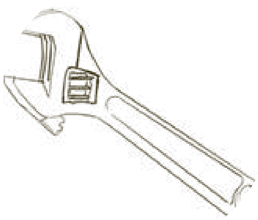
1. Biomaterial basics



2. Biomaterial and its matrix



3. Process and production



4. Tool development

5. Product development

7.1 BIOMATERIALS BASICS

Animal and vegetal Bio-resin

An initial approach to biomaterials was made with bio-resins, where two different recipes were used (APENDIX A), a vegetable one and an animal one, where agar-agar and gelatin were used respectively. A basic mixture of water, glycerin and a plasticizer were made and additional ingredients such as oregano, cinnamon, curcuma, and pepper were used to define different textures and colors to the samples

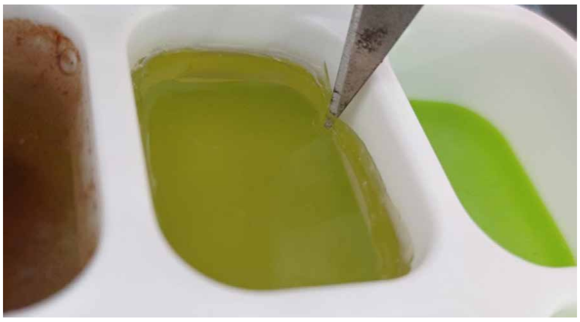


Figure 1 - (1) Bio-resin poured in ice cube trays after one night of drying, (2) Extraction of plane gelatine-based bio-resin. (3) Plane gelatine bio-resin appearance. (4) Curcuma and agar-agar bio-resin appearance.

The mixtures were molded in an ice cube tray, which has a top rigid plastic section and the bottom made of silicone for easier push extraction. Given the amount of mixture present on the recipe, a dying process with raw spices was tested, giving a different look to each of the samples. After one night of natural drying the samples could be carefully removed with the help, in this case, of a cutter knife.

For the gelatin-based bio-resin the texture was gummy-like, therefore it was soft and malleable, and somewhat moist. The appearance was semi-transparent with a yellowish color. On the other hand, for the agar-agar bio-resin the surface was more porous and much moister, seeming much more fragile than the gelatin based one. The appearance was opaque, and white.

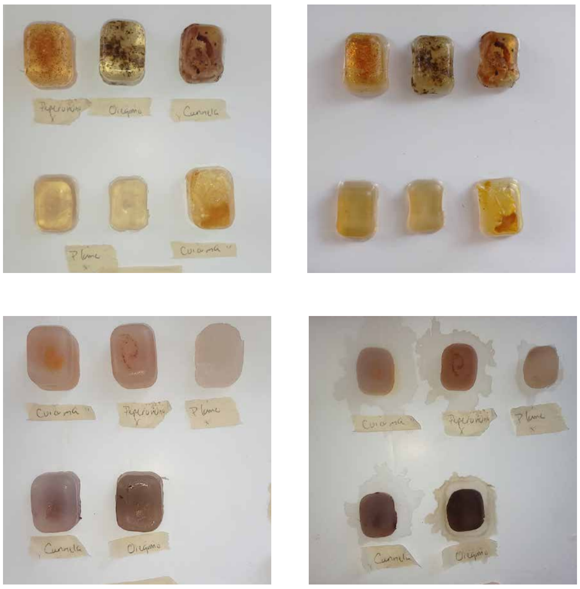


Figure 2 – (1) Bioresin samples from gelatin base after mold extraction, (2) Bioresin samples from gelatin base after six days of drying, (3) Bioresin samples from agar-agar base after mold extraction, (4) Bioresin samples from agar-agar base after six days of drying.

The samples needed to be taken out of the mold because they were not drying completely, therefore once taken out they were able to dry in a more uniform way. Once taken out from the mold, the samples were left drying for six additional days to reach stability. As seen in Figure 2-(1) and Figure 2-(2), for the gelatin-based resin the reduction in size was somewhat a fourth of the initial size, shrinking on the sizes giving a curved appearance near the edges. These pieces, once dried, are completely solid and lose the rubbery-like feeling they once had. On the other hand, the agar-agar samples reduced almost half of their initial size, it can be seen the amount of water they save and keep losing during the drying process. Additionally, they seem fragile, still soft, and malleable, not hard like its gelatin equal. Although the spice did give the samples a different tonality and a character to each piece, some of them affected the behavior of drying and unmolding. The spices were placed once poured the mixture into the mold, some before, some after. For the samples in which it was placed the spices before, for example of the cinnamon, the mixture wasn't able to attach correctly to the mold, additionally, since the cinnamon is dry and absorbs moisture, when unmolding the piece, it cracked since it stopped the mixture to mix and dry homogenously.

Bioplastic from corn starch

The next polymer tested was corn starch. Two basic recipes (APENDIX A – Recipe 1) of corn starch, glycerol, water, and vinegar were developed to obtain a biofilm. The two recipes differed in the proportion of starch and glycerin present in the mix, 6% and 9% for the first one and 2% to 5% for the second one, respectively. The first recipe was poured in two different recipients, the first sample was spilled on a tray and the second one on a homemade mold made out of a foam board base and scotch for the borders (crafty but effective). The second recipe was poured over the just in the handmade mold since it was too liquid to be led in a flat surface.

Figure 3 - Evolution of the recipe 1, poured in a tray. From left to right: day 1, day 3 and day 7.

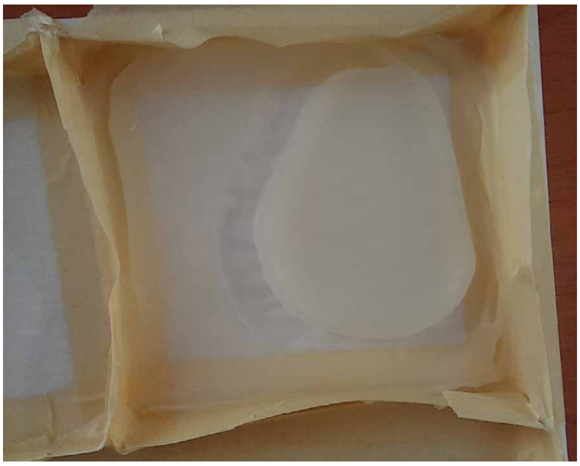


Figure 4 - Evolution of the recipe 1 and 2, poured in homemade mold. From left to right: day 1, day 3 and day 4.

After five two of natural drying, the second recipe was still liquid, a little plastic film on its top started to appear but nothing more. On the other hand, the first recipe started to set d took a pudding-like consistence. After another two days, meaning on the fourth day of drying, the second recipe was still liquid, and no additional sign of setting was seen in the mix. The first recipe continued to dry and set, but the pieces were starting to break. At the beginning it was thought that the scotch walls were causing the detachment, but seeing the mixture poured on the tray, a little crack on the side also started to appear Figure 4-2.

After more days of drying, around day seven, the second recipe was still liquid and by this time thrown away. Differently, the first one was already set, and had changed to a transparent bubbly color. Both of the mixtures (the one poured on the mold and the one poured on the tray) broke, meaning the bonds generated weren't strong enough to keep together the piece, and also the friction generated in the recipient, constraint the shrinking of the piece while drying.

This first findings started were useful to start defining some limitations that might have the biomaterials, what variables might be changed on the recipe to improve their result, and additionally what pain-points can be addressed while developing the tool.

7.2 BIOMATERIALS AND ITS MATRIX

Once having had an initial approach to the basic recipes of biomaterials, introducing fillers to the mixtures was the next step to analyze. An initial screening process was made to identify which fillers might be convenient to use. Criterions such as ease of accessibility, ease of processability, amount of waste generated through the year, and composability (more than biodegradability).
Sugar bioplastic

The initial recipe developed was developed with agar-agar, glycerol, corn starch, sugar powder and water (APENDIX – Recipe 3). For this recipe, different formal experiments were made trying to pour the mixture in different ways, different shapes, and see how the material would behave in each of those.

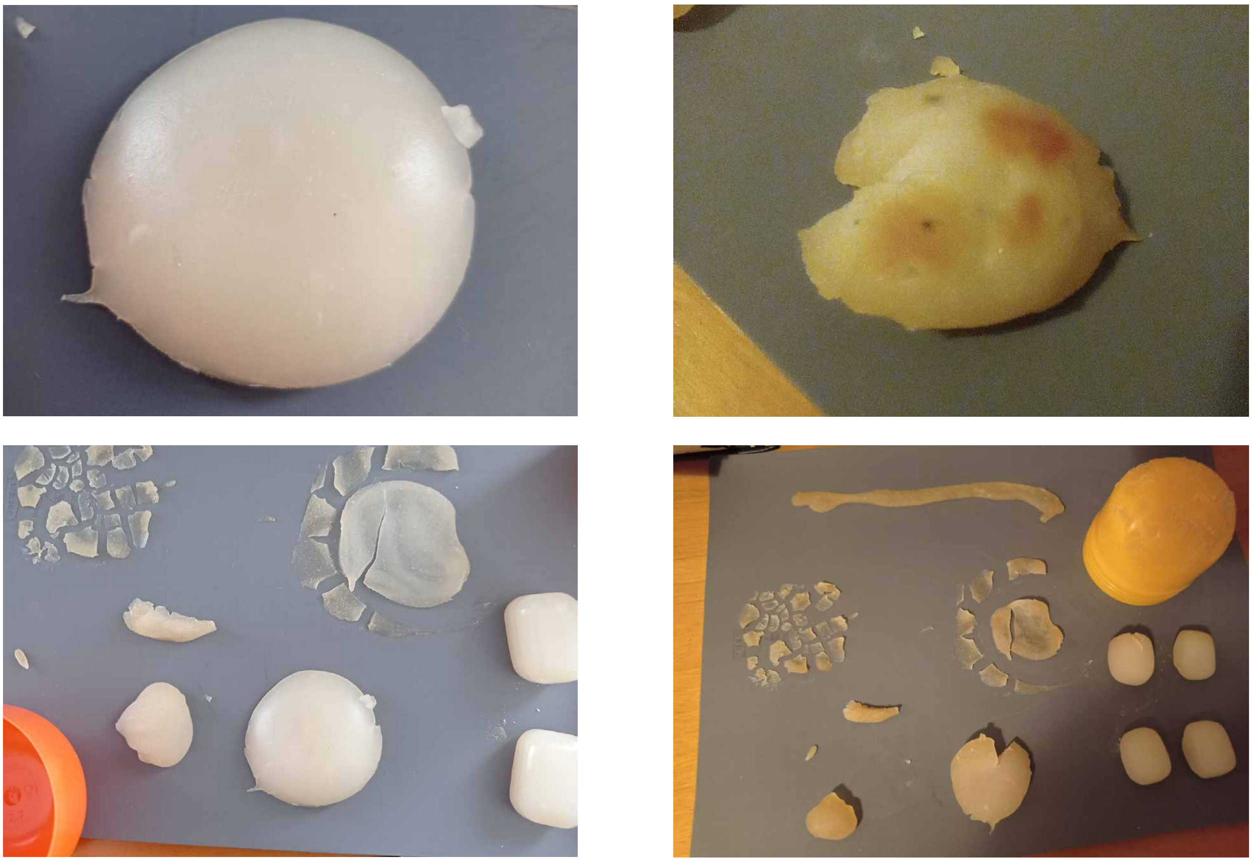


Figure 5. (1) Day one of the unmoulded recipe, moulded inside a cocoon like shape (2) Day three of unmoulded recipe inside a cocoon like shape, (3) More sugar base bioplastic samples day one, (4) More sugar base bioplastic day three

The setting time for this recipe was three days, where, as seen in the pictures, mold proliferation started to appear. As it is stated in the book Performance of Bio-based materials by Dennis Jones and Christian Brischke. the proliferation of mold in these types of materials can be defined mainly by moisture, temperature, type of substrate, and exposure, whereas less important factors are mold spores, pH, light, oxygen, and surface roughness of the material. Now for the pieces that most amount of mold appeared, where the bigger and thicker ones like Figure 5-1. In this case, the mold started appearing mostly on the inside of the piece, on the part further from the surface, therefore the part which took longer to dry. In this case, since the substrate is sugar, therefore glucose, it can be feeding or helping the mold growth (an additional study on substrate and growth has to be done to verify this assumption). Considering this, it is responsible to assume that due to the amount of water present in the mixture, and the amount of time it takes to dry, mold proliferation begins to be a problem; another limitation found, at least when drying the piece naturally.

Coffee + sodium alginate

Moving forward, a recipe made with coffee residues and sodium alginate (APENDIX B – Recipe 4) was developed. In this case a similar handmade mold was created for the pouring of the mixture providing a bigger area of spread, looking to develop a bigger sheet of plastic. In this case, the use of vinegar works to accelerate the process of gelling of the mixture, and in the recipe is sprayed once poured the material. A base of vinegar was placed on the bottom and on the corners of the mold to allow an even drying process.

Figure 6. Sodium alginate base coffee samples - (Row 1) Day 1, (Row 2) Day 2, (Row 3) Day 3, (Row 4) Day 5

For the squared mold a thicker mixture was poured (~ 3 mm), whereas the rectangular mold was filled leaving a thinner layer of mixture (~ 1 mm). Although this happened because not enough mix was made to complete the second mold, it allowed us to observe the differences in the behavior between the two. Hence, as seen in the pictures, the mixture with the thicker layer, during the drying process, cracked in a circular shape. The second pour dried more uniformly and without many cracks. Even though some cracks appeared in both samples the results were good, where the feeling of the material was plastic like, hard but malleable, and semitransparent. In this case, the coffee didn't act as a binder, or didn't give a structural purpose to the same but more an aesthetic one, providing a coffee tincture with granular feeling and look.

Agar-agar + coffee

Continuing with coffee as the filler, the next recipe used agar-agar as the polymeric agent (Appendix B – Recipe 9.3). For this pouring a new mold was constructed, made with two pieces of plexiglass, the top one cut with eight squared holes made of 10x10cm, and the bottom one flat working as support. In this case the plexiglass was useful to avoid the absorption of any water of the material, or later sticking to the sample, which initially happened with the homemade mold.

Figure 7. Samples of agar-agar coffee base bioplastic

For this recipe, only one overnight of drying was enough. In this case, as happened with the bio-resin made with the same base, it shrunk during its drying process, in this case, cracking the whole sample in different little pieces. Although is interesting the flake-like shape that came out from the mixture, the result wasn't as expected.

Coffee + agar-agar + MC

Now, trying different solutions for the agar-agar to work, another binder was added. In this case, methylcellulose (MC) was used. This latter was chosen due to its additional binding properties. MC is a cellulose derived from wood and has good thickener, binder, and emulsifier properties (Kääriäinen, Tervinen, Vuorinen, & Riutta, 2020) that can aid the cracking problem having on previous sample (APENDIX B – Recipe 9.1 – 9.2).

Figure 8. Agar agar + MC Coffe recipe afafter drying process.

Now, although the MC gave a thicker and more malleable property to the sample, the cracking still appeared. During the manipulation process, the sample seems wet enough, but during the drying process it becomes fragile, more like a cake than a piece of cloth. In this case, the sample didn't crack by itself, but when tried to being lifted.

Coffee + gelatin

Gelatin was the next polymer tried with the coffee waste filler. From previous experiments (e.g., animal-based bio-resin) it was stablished the efficiency of gelatin as a binder. As it happened for the initial recipes, the samples, although they didn't crack, they did warp. In this case since the thickness was uniform along the sample, the sheet was bent in a concave shape leaving its thickness uniform. Although the original recipe was made with eggshells, it still worked with coffee as a filler (the eggshell one will be discussed further along this section). For this recipe there was no plasticizer present, therefore this also contributed to the final rigidity of the object.

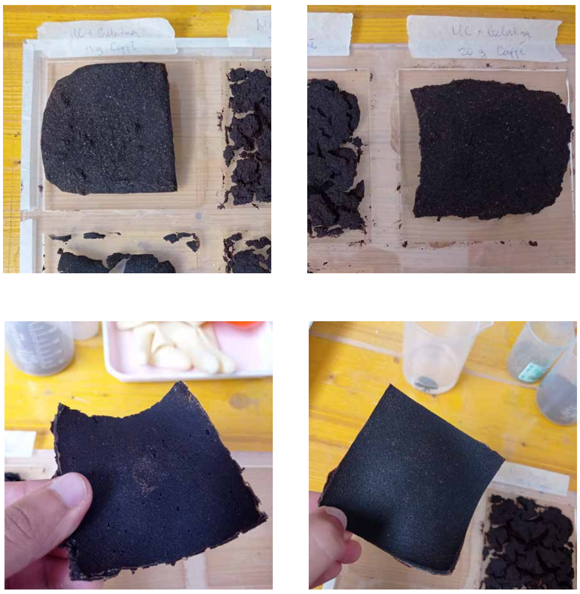


Figure 8. Agar agar + MC Coffe recipe afafter drying process.

Now, considering the good structural result of the sample a different molding process was started to being considered to reach a final form. Seeing the warpage of the sample the molding process had to somehow avoid this from happening (if not desired of course). Noting this, it is important to note that, depending on its use, the warpage can be seen as an advantage (e.g., artistic pieces), being a property that gives a different form and finish to the final shape, although unpredictable it is quite interesting.

Coffee + starch + MC

For this recipe another attempt for MC was tried, this time mixed with corn starch and coffee. For this case an additional step was approached in order to optimize the mixture use. Although the same base was made, a different concentration of coffee was placed on three different samples (APPENDIX B – Recipe 6).

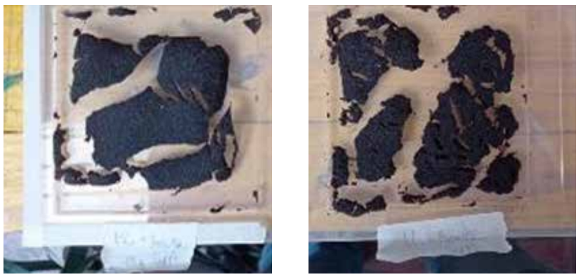


Figure 10. Recipe of starch + MC with coffee base after drying process

As seen in the results, although te samples cracked it can be seen how with the more concentration of coffee a less aggressive crack appeared. This gives an idea on how fillers can be able to hold the bonding tensions generated during the drying process, meaning a substrate with larger fibers instead of just particulate or granular fillers could provide a tighter binding.

Sodium alginate + coffee

For the next experimentation sample, the same approach used for the corn starch plus MC was used, where different concentrations of coffee were placed to the same mixture base to observe and analyze the property's changes in the samples. For this mixture, coffee, sodium alginate, glycerin, water, and vinegar were used.

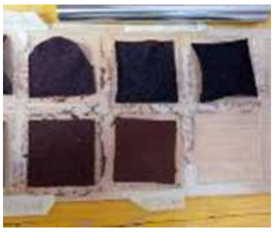


Figure 11. Sodium alginate + coffee base recipes (1) Top left, (2) Side, (3) Top right views.

As happened with the initial sample of sodium alginate (Figure 11-2), their binding properties are outstanding. All the different samples made, after a drying process of four days, worked out fine and didn't crack, just warped depending on the concentration of coffee for each one. The samples with more coffee concentration were the ones that warped the least, being consistent with the finding on the previous experiment, meaning the filler provides certain stability to the sample, stopping it from cracking or in this case from warping. The ending samples had a leather like feeling for the ones with less coffee concentration and a more foamy-like one for the ones with more concentration.

Having these results, additional analysis was developed to give more conclusions around them. First of all, a measurement of all the samples was made, considering area, thickness, and volume. This, to understand how by changing the filler percentage, the shrinkage process will be affected.

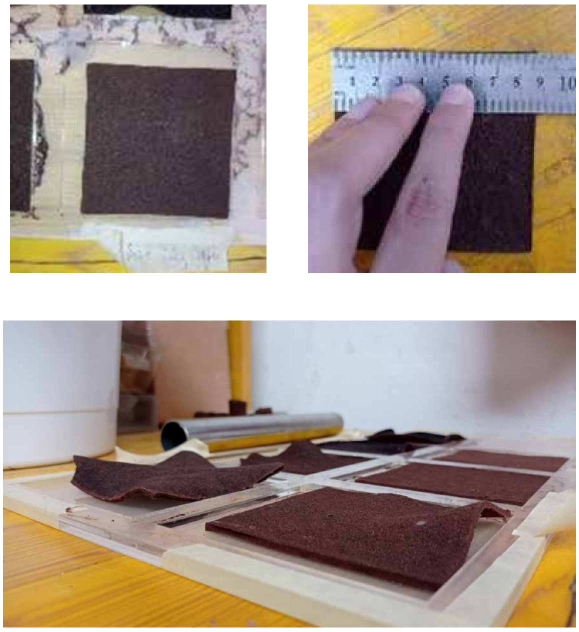


Figure 12. (1) Top view of coffee-based biomaterial, (2) Measuring retraction of coffee biomaterial sample, (3) Coffee plus sodium alginate samples after drying.

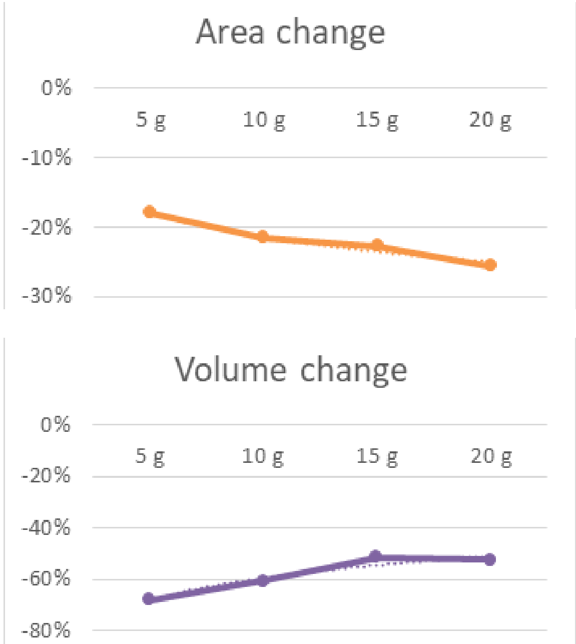


Figure 13. (1) Area and (2) volume variation charts, regarding amount of filler placed on coffee and sodium alginate recipe.

As seen in the different area and volume charts, the grams, hence concentration of filler, does have a relation between the area and volume shrinkage. In the case of the area, as going up with the percentage of filler, the sides will shrink much more than what it reduces in thickness or in volume. Whereas, for the samples that had less percentage of filler didn't shrink as much on their sides but did lose more thickness and volume. This occurs since the filler, as seen previously, provides more structure to the material, rendering it more stable. Supporting this, as seen in Figure 13 – 3, the percentage of filler renders less flexible the material as it is increased. Additionally in the case of coffee, a substrate can influence due to its absorption percentage allowing or avoiding water to escape from the sample modifying the final looks and properties of the piece.

This analysis proofs useful to understand rates of shrinkage, in this case for this recipe, and to forecast the final size of the piece being made, considering the percentage of filler the mixture is having. Additional studies should be made, not only for this single recipe, but for proven recipes to standardize and have a more controlled production process. Finally, it is important to note that shrinkage can also be affected by environmental factors, therefore humidity, temperature and drying method will nominally affect these findings.

Corn starch + Sawdust

Understanding how the fillers play a crucial role in the manufacturing of biomaterials additional experimentation was developed. As stated previously, even though the filler adds structure to the material, the form of the same might affect the adhering and binding during the drying process. Since granulated fillers were tested, an assessment with more fibrous ones was approached. Materials such as wool, grass or sawdust were considered. Sawdust, due to its easiness of obtention, was chosen first to experiment with.
The initial recipe tested was made with sodium alginate, glycerin, water and vinegar. For this experiment the sawdust was taken from the vacuum cleaner of a wood working shop where it was mixed with some regular dust, and particle

chips from metal grinding. The idea was initially to test the binding properties on the filler itself trying to get the longest fibers possible from the sample, therefore an initial screening and sieving was made to clean and obtain the wanted type of filler.

Figure 14. Corn starch + sawdust sample after drying process (APPENDIX B – Recipe 5.1)

Taking back the results from the initial corn starch recipe, although the end product resulted in a good-looking plastic, cracks appeared during the drying process. In this case a similar situation occurred, but, due to the filler, although cracks appeared on the material, it remained stuck together without breaking apart. The material was poured on the plexiglass flat mold and left to dry for three days. Additional tests were made with this material, that will be discussed in the following *Tooling development section.*

Sodium alginate + sawdust

Additional tests were made with sawdust, being one with sodium alginate and another one with carboxymethyl cellulose (CMC). Both of the recipes turned out good, since none of them cracked, but the results on both of them were quite different. On previous results it was seen how the sodium alginate recipe made the samples soft and malleable, depending on the amount of filler of course. For the sodium alginate test the percentage of sawdust used was about 13%, a percentage lower than the minimum percentage used in the tests for the coffee and sodium alginate sample. In this case, even though the percentage in mass was less than the one for coffee, the result was a sheet sample as hard as the hardest of the coffee samples. This happened because sawdust is much dryer, therefore captures more moisture of the mixture. Additionally, the density of coffee waste is much higher than for saw dust, meaning that 10 g of coffee saw dust will occupy much less volume than 10 g of saw dust. It is interesting to see the difference between fillers and how they react with a similar mixture showcasing properties that have to be analyzed each time when developing a new product.

Figure 15. Sodium alginate + sawdust recipe after drying process (APPENDIX B – Recipe 4.5)

CMC + sawdust

Now, the Carboxymethyl Cellulose (CMC) is one of the most common water-soluble cellulose derivate, and the difference between the two is that unlike CMC, MC is a non-ionic polymer, therefore is suitable binder for all particles, independent of their ionic charge (Kääriäinen, Tervinen, Vuorinen, & Riutta, 2020). There is an interesting study showing the difference between the two of them regarding bioplastic, also mixed in different ratios with starch polymers, considering plasticizers such as glycerol and polymethyl glycol (PEG) (E. Aytunga Arık Kibar, 2012).
The result of the mixture resulted in a stiff but brittle material, a mixture between cork and Styrofoam, that although delicate, didn't crack during its drying process. The previous article exposed show different ratios of mixtures combined with corn starch, stating how MC and CMC can increase their mechanical properties. Future experimentation with these mixes can be done in order to explore its product possibilities, from hanging boards, to packaging, replacing damaging plastics in this environment such as Styrofoam.

Figure 16. Views of CMC + sawdust samples after drying process (APPENDIX B - Recipe 10.1)

Grass + corn starch

One of the last recipes developed was grass and corn starch. In this case the approach was to look and experiment with a filler that had longer fibers, considering the hypothesis initially made and understand the behavior of a new filler. As corn starch had one of the easiest recipes to replicate and also was among the best results obtained, this recipe was chosen.

Figure 17. Failed experiments of grass + corn starch biomaterial (APPENDIX B-5.1 -BASE)

Right during the production of the recipe there were some mixing problems, since the grass taken, even though it was already cut, it saved some of its moisture therefore making the mixture more liquid and viscous. Because of this it was possible to pour the mixture into the plexiglass molds, but to shape it like molding it with plaster. A ball of grass, after struggling with how viscous the mixture was, developed. Although a different sample, it resulted stiff, hard and no cracks of any sign was seen, so in one hand the idea of stating that a filler with longer fibers allowed better binding and could reduce cracks formation during the drying process, the mixture is difficult to manage. On the next section, the molding process for this recipe will be analyzed.

7.3 PROCESS AND PRODUCTION

As the objective for the thesis was to develop a semi-finished or finished product, the processes that were analyzed looked to mainly develop structural pieces. Pieces that can work as a final product themselves, or pieces that, once fabricated, could be followingly labored, either by a shaping and/or joining processes to become a final product. Even though different processes were assessed, the focus was placed on molding and its different subdivisions due to its facility to replicate, and to the outcomes it allowed to obtain.

7.3.1 Conventional molding

As already seen in the previous sections, conventional molding was already used to obtain the samples for the different biomaterials' recipes, from handmade scotch ones, acrylic laser cut, and silicone. Some benefits of these conventional moldings are the possibility to replicate different samples keeping the shape variable constraint.

Starting with flat molds, these are the most beneficial in terms of obtaining uniform samples. In the case of the mold developed for this thesis, since the area exposed to the air was far greater than the thickness of the material, it was much easier for the sample to dry in a homogenous matter.

Talking about homemade molds, it is important to have in mind certain considerations. First of all, the material which it is going to be made out of shouldn't be porous or absorbent, therefore wood, cardboard, foamboard, are not good options since they will absorb the humidity of the mixture and alter the final result. On the other hand, materials such as aluminum, steel, acrylic, since are hydrophobic, will maintain their shape and will give the best results for the samples.

Figure 18. (1-2) Saw dust + corn starch bricks samples, (3) Bioresin gelatine base with spices recipe samples, (4) Starch base bioplastic sample, (5) Agar -agar + coffee base after pouring sample.

Now, using already made molds, such as ice cube trays or pastry molds are useful because they frequently are made in latex, a material easy for demolding and to be sturdy enough to keep a certain shape. They also come in different shapes and sizes, so different shaping tests can be done. When using these types of molds is important to understand that if the goal is to make a solid shape, e.g., a cube, a block, a cylinder, the drying process will be affected, since the ratio of area exposed vs thickness of the sample will be minimum, therefore delaying the drying process, increasing the chance of cracking and mold growth. As seen in Figure 18 – 2, after the bricks made of sawdust and corn starch were somehow dry on the top, they had to be removed from the mold to allow the complete drying of the piece. This is a problem that will have to be addressed and will be common in other types of molding.

7.3.2 Shape molding

Given some composition of the mixtures being made, it was noticeable how many were malleable, meaning it was possible to, once the mixture was cold (if heated), to sculpt and play with them giving them any shape desired. After several trials, the recipes that what a starch polymeric based were the ones that could easily be malleable, so shapes made out of starch and coffee, sawdust or grass were attempted.

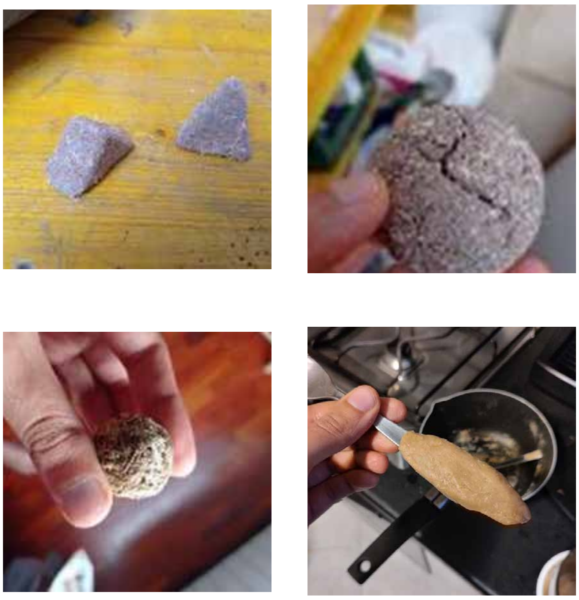


Figure 19. Sculping experimentation (1) Sawdust pyramids, (2) Sawdust sphere (3) Grass sphere (4) Fork handle

For the next shaping process, an attempt to mold the material for it to take different shapes was taken. A shape was the essential and basic form looked for. For this process a recipe of coffee with corn starch (APPENDIX B – Recipe 5.2) and sawdust with corn starch were placed to test. For the mold, two vases were covered with oil as an unmoulding agent, then their outer parts were covered with the respective mixtures.

Figure 20. (1-2) Moulding glass process with corn starch + coffee recipe, (3-4) Moulding small glass process with corn starch + sawdust recipe.

After two days of drying the two pieces showed prominent cracks. The sample with coffee filler broke when tried to unmould, whilst the one with sawdust was able to stay together. When unmoulded, the inside part was still soft and moist, therefore it had to be separated to accomplish a complete drying of the piece. After 3 more days, the piece completely dried and became almost rock solid.

This result, one more time, allowed to showcase the structural benefits a filler like the sawdust has over a granulate one like coffee.

This type of moulding is problematic since when the material is drying it will contract towards the mold itself, and if the mold is solid-unmovable, the material will be constricted, and without range of movement the tension generated during the drying process is high enough to break the bonds

7.3.3 Extrusion

Seeing the good results obtained with the sodium alginate and the coffee recipe an extrusion test was attempted. At the beginning the mixture wasn't viscous enough, therefore a drying process with a fabric cloth had to be made (Figure 20-1). When attempting to extrude the first time, due to its liquidity (Figure 20 – 2), no solid shape or piece was made, but as drying the mixture more solid pieces started to come out. An additional test was made adding sawdust in order to dry the mixture even more. The final result was broken pieces of the sodium alginate, which due to the extreme drying process were too brittle to work with.

Figure 21. Extrusion experiments with sodium alginate + coffee recipe (1) Initial mix, (2) Extrusion process, (3-4) Sieving process, (5-7) Extrusion process 2, (8-9) Extrusion process with sawdust.

A final extrusion attempt was made with just sawdust and corn starch (APPENDIX B – Recipe 5.5 - BASE). In this case, due to the viscosity of the mixture, it being not liquid enough, the material was not allowed to exit the extruder uniformly. In this situation, since the molding processes were showing more promising results than the extrusion ones, it was decided to leave the latter and focus on the study of molding processes for the biomaterials.

Figure 22. Gelatine + coffee compression experimentation (1) Saw dust first day (2) Sawdust after drying process, (3-7) Corn starch + sawdust compression experimentation.

7.3.4 Compression molding

After seeing how different recipes 7 and 5 (APPENDIX B) worked, such as starch and sawdust and coffee with gelatin (APPENDIX B – Recipe 7.1), a bigger attempt was tried for both of them. The initial experiment involved recipe 1 – gelatin and coffee, where a mixture of 200 g was made in order to make a bowl. The mixture was placed between two glass bowls, wrapped around film paper to allow easier extraction, and by pressuring, the mixture with the two-glass bowls it was possible to replicate their shape. Due to the pressure generated between the two pieces, and the film paper, the piece was able to be unmolded, keep its bowl-like shape, and with the possibility to completely dry. The same process was replicated with the second recipe (APPENDIX B – Recipe 5.1), where the same compression process was done. For both the recipes the pieces were extracted thanks to the film and the compression process, almost without losing their form. Now after the drying process, the sawdust mix cracked in the middle, and the one of coffee warped giving an interesting texture to the vase. Here, certain shapes were already being obtained, mainly with the aid of compression molding.

After having these results, a bigger attempt was made, to develop a bowl 40 cm in diameter and 10 cm of depth. For this process it was decided to use the recipe of sawdust and corn starch, due to its easiness of development and practicality, since it required a large amount of ingredients

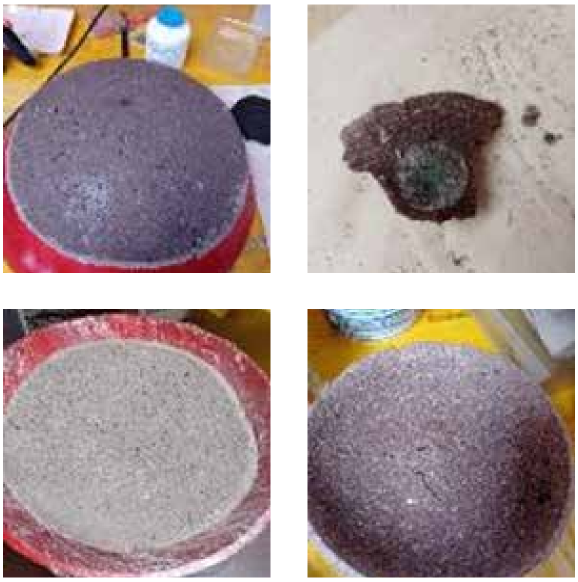


Figure 23. Big bowl test with sawdust + corn starch recipe

Since for this piece only one bowl with the required dimensions was available, the piece had to be placed by hand on the reference bowl and no pressure could be done. The piece, due to its size started to present cracks since its drying wasn't uniform, additionally, the part that was facing the bowl, after 2 days of drying was still moist. This led to mold proliferation and finally the spoilage of the piece. In this instance, more experimentation but on a smaller scale continues to be done.

At this point of the research there were some issues identified during the molding of biomaterials that had to be addresses to obtain a finished or semi-finished product:

1) The drying process is the step that takes considerably more time of the whole production, and the one was complications on the piece forming appear.

2) Solid pieces do not dry completely if left on a mold, allowing the appearance of cracks and mold proliferation.

3) Sculpt molding, although allows a good drying process being all the piece uncovered, does not lead to the best aesthetic or precise results. This process will depend on the ability of the person to shape the piece.

4) A rigid mold, mainly when inverse molding, will make the piece crack when shrinking during the drying process, therefore keeping its shape along all the molding process is a challenge.

In the following processes shown, the main objective was to aboard the previously presented issues, arriving at a final produced piece.

7.3.5 Clay molding

An initial process was attempted to be developed where the piece could be inside the mold and accelerate its drying process without the need of unmolding the piece beforehand. One of the first approaches made were to develop a clay mold in which a mixture could be compressed and placed in a direct heat source so the piece could dry. For this, a negative of the piece that was looked to be done was milled in a block of molding wax. The piece was modeled looking to maximize the basic principles of compression molding, meaning wide tapered angles, and a simple shape for easiness of extraction - *Refer to (Groover, 2013) for a thorough explanation on compression molding* -. After the piece was milled, two negative pieces from clay were made. For this, an acrylic box was laser cut to contain the clay for the negative piece, the box was sealed with glue to the wax mold, and additional hot glue was used to seal any holes where the liquid clay may run off. After two hours of drying one piece was done. The same process was repeated for the second one.

Once the molds were ready the mixture of the biomaterial had to be done. For this case the recipe (APPENDIX B – 5.1 BASE) of cut grass and corn starch was used. Since as already since, the corn starch mixtures are allowed to be hand-handled due to their malleability, the mixture was placed in all the corners of the mold. At this point, due to the length of the grass, plus the viscosity of the mix, some spots on the mold were hard to cover and reach. Once the mixture was placed, with two clamps the mold was compressed and closed.
Having the piece already compressed inside the mold, the first attempt to dry it was in the vacuum chamber. For silicone or resin molded processes, vacuum chambers are used to extract the air bubbles generated on the mix, to guarantee

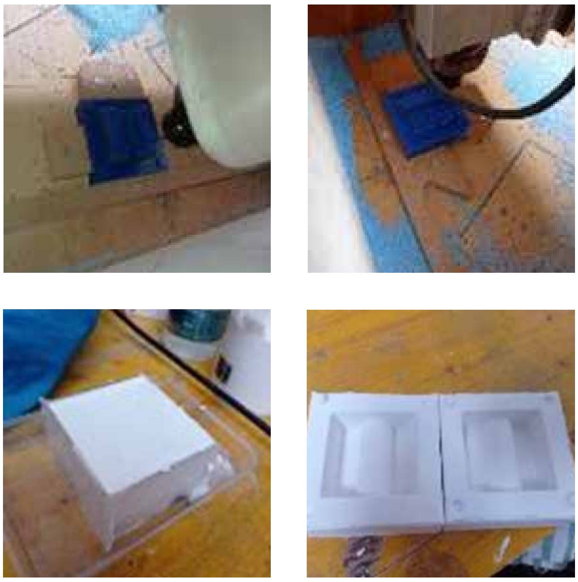


Figure 24. Clay moulding manufacturing process

Figure 25. Moulding grass + corn-starch recipe, process experimentation

a better molded result. For this situation it was used to increase the drying process. After five minutes in the vacuum the mixture showed no change. Since the mixture was indeed steel very viscous, and the vacuum showed better results on more liquid mixtures, a different approach was taken.

The clay once dried is one of the highest fire-resistant materials there are, being able to hold over 1,000°C. Considering the properties of the materials it was possible to dry the material by overheating it, in this case, in the oven. The piece was then left in an oven, still clamped for 4 hours at 80° (since the idea was to dry the material and not burn it, it was not necessary to go past this temperature).

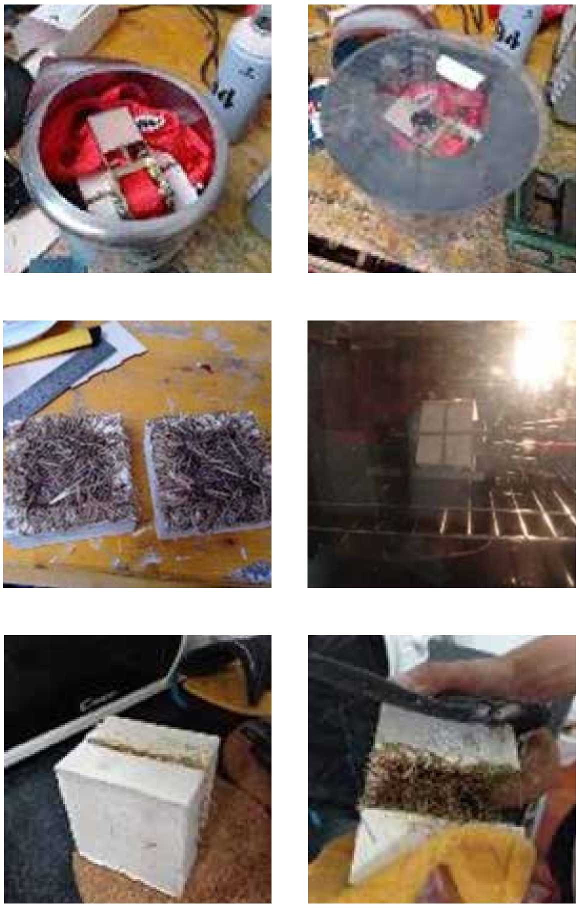


Figure 26. Drying and unmoulding procedure for grass + corn-starch

After the drying process, the material did not remain stuck, and instead two half molds resulted. Once completely dried, the grass attached so hardly to the clay mold that it was necessary to break the molds to obtain the pieces. After breaking the mold, a broken grass piece came out that didn't reflect all the work and hours placed on the mold.

7.3.6 3D Printing molding

Now, with the same idea of generating a compression molded piece and allowing it to dry inside the mold, 3D printing started being experimented with. Designer Kazuhiko Hayakawa created a method to efficiently 3D-print a base mold mesh for molded pulp products, allowing the users to create planters of various sizes (Hayakawa, 2015). In these products Hayakawa plays with the infill of the 3D printing to create a mesh that allows the pulp to dry while being molded at the same time.

Image 38. 3D Printing moulds for recycled paper pulp products (Hayakawa, 2015)

Taking as a reference Hayakawa, the mold pieces were developed. For the first prototype, a mold of a Lego brick was designed, where no top or bottom walls were left for the printing and an infill of 80% was defined. In this case the main idea was to allow an open enough infill gap for the print allowing air to flow through the piece but a gap small enough to avoid the mixture slipping through the holes. The sampling was made with the recipe (APPENDIX B – Recipe 5.1) of sawdust and corn starch. After molding, the piece was left drying for day 2 days, where although the piece formed well, no sign of drying was shown. The infill gap left was still to straight to allow some air to flow. Additionally, the complexity of the piece had certain fixtures avoiding the air to circulate correctly.

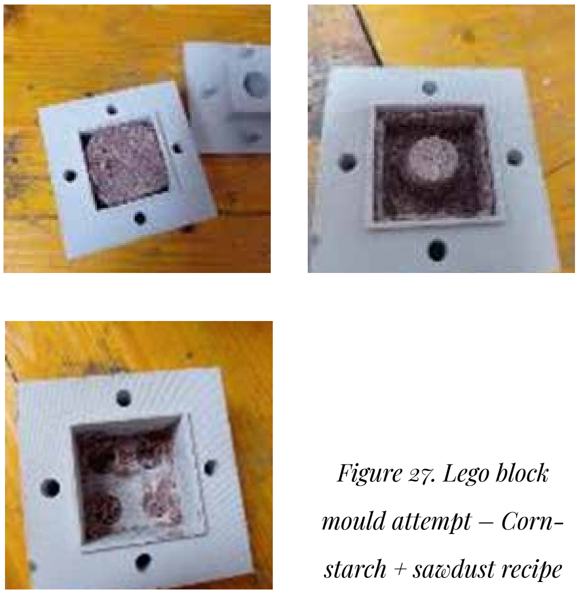


Figure 27. Lego block mould attempt – Cornstarch + sawdust recipe

A second attempt was developed with a new and simpler mold. In this case a simple pyramid piece was designed to prove if the concept developed by Hayakawa was applicable to biomaterial pieces. For the 3D printing mold a different technique was used, instead of a two piece a three piece mold was developed, and a gradual infill was placed having a larger mesh at the edges of the mold and smaller ones as the print reaches the main mold chamber. This was attempted to ease the extraction of the piece, and increase the airflow that reaches the mixture, while at the same time defining enough the molding section so no mixture will slip through the gaps, and the piece could be well defined. For the printing process, the lateral walls well left to provide structural support, since the mold will be compressed on the vertical axis. The mold was left with two wings to allow better clamping on its side.

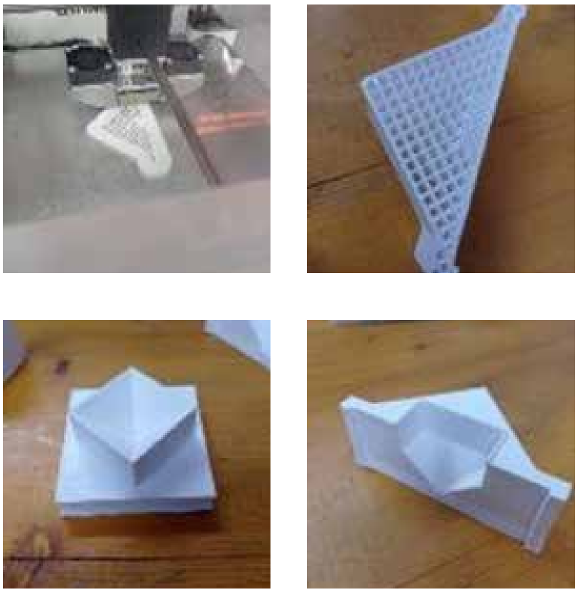


Figure 28. 3D Printed Breathable mould design for biomaterials

For the molding process, unmolding agent was placed on the main molding chamber to facilitate unmodling. The sodium alginate and coffe recipe (APPENDIX B – Recipe 4.1) was used for this sample. Once closed, and clamped, the mold was left besides a fan providing air to aid the drying process during five days. Once opened the mold, the piece was still moist and some sides of the pyramid had a thick fungal layer. It is unclear why the mold only appeared in one side of the piece, but still it was not a good result for the experiment. The piece was able to be unmolded since no crack made it break and the mixture has binded. After completely drying it was possible to sand the piece and remove the mold from it, ending in a fuzzy soft pyramid.

The second attempt showed that the mesh strategy for a closed compression mold does not

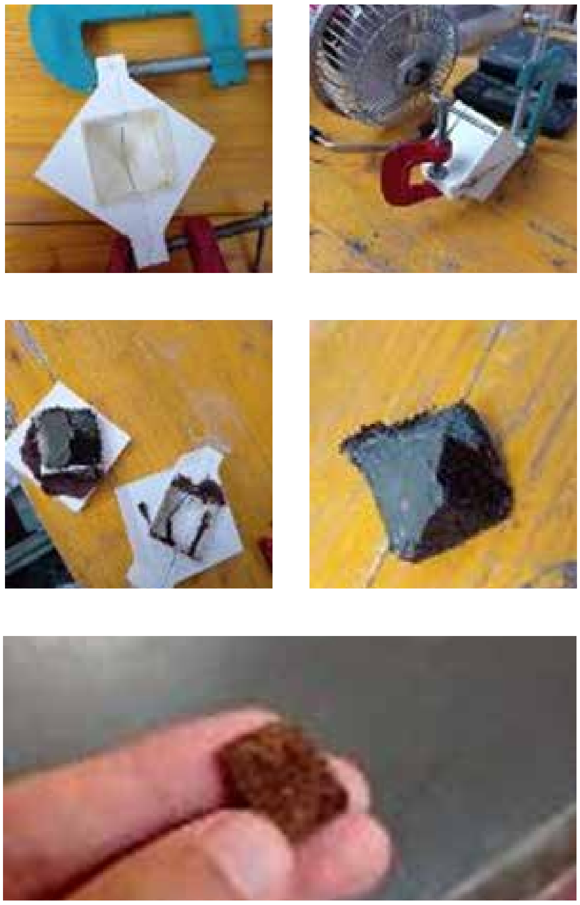


Figure 29. Breathable moulding test with sodium alginate + coffee recipe

work properly. Even with an air fan placed on the sampe for fice days of drying the piece at the end of this time was still moist. No actual way of releasing water without heating was possible. Additionally, although the mesh allows the mold to breath more and receive more air, it is still not enough to dry completely the sample. Finally, if the mixture is somehow liquid, it will most probably clog the mesh holes cancelling completely the breathing function that was supposed to initially provide the mesh.

Considering the latter a different attempt with the mold was done. Instead of leaving the mold closed for various days waiting for it to dry, more pressure and more mixture was placed on the molding process. For this attempt, since the sodium alginate recipe was too liquid, a sawdust and sodium alginate recipe (APPENDIX B – Recipe 4.5) was used instead. The mold was filled and clamped several times to increase the density of the final piece by adding the most amount of material possible. After clamping the side wings of the mold, its top piece was clamped with a bench bise placing two waste plywood chips to protect the mold from damaging.This way of clamping allowed to extract the excess of water of the mixture. After two hours, the mold was unclamped and the piece was binded well enough that it could be removed by hand, with no cracks or mold present. Although still moist, once taken out of the mold the piece was allowed to completely dry, which for this one took 1 additional day.

The piece once dried was allowed to be sanded but ended being fuzzy. Due to the type of recipe used, the feeling of the piece was soft and cushiony, and although it standed sanding the corners were still fragile risking breakage.

Figure 30. Compression moulding test - sodium alginate + sawdust recipe

At this moment the decision to work with sawdust was taken, due to the good molding properties it showed and to the possibilities regarding circular design it provide. *Chapter 5: Sawdust,* already discussed and support this affirmation.

Due to the success of the previous mold, a second one with a usable and more complex shape was made, in this case the mold of a small glass. Now, considering that the sodium alginate and sawdust recipe resulted soft, a recipe which end product was harder was attempted, therefore recipe (APPENDIX B – Recipe 5.5) sawdust and corn starch was chosen.

In this case for the 3D printing there was no need to remove top or bottom layer and adding gradual infill since it was already decided the mesh strategy was not useful for this type of molding. For this molding process the same steps were followed as the previous example: preparation of the mold, preparation of the mix, clamping and after two hours extract the mold to let dry. Once completely dry a trimming process of the excess material could be done, rendering more appealing the final product.

After three days of drying, the piece was completely rigid and ready to use. Although the drying process is still long, being able to separate the piece from the mold just after two hours of drying, allows the mold to be reused more quickly and to have several pieces drying at the same time, being it a substantial improvement.

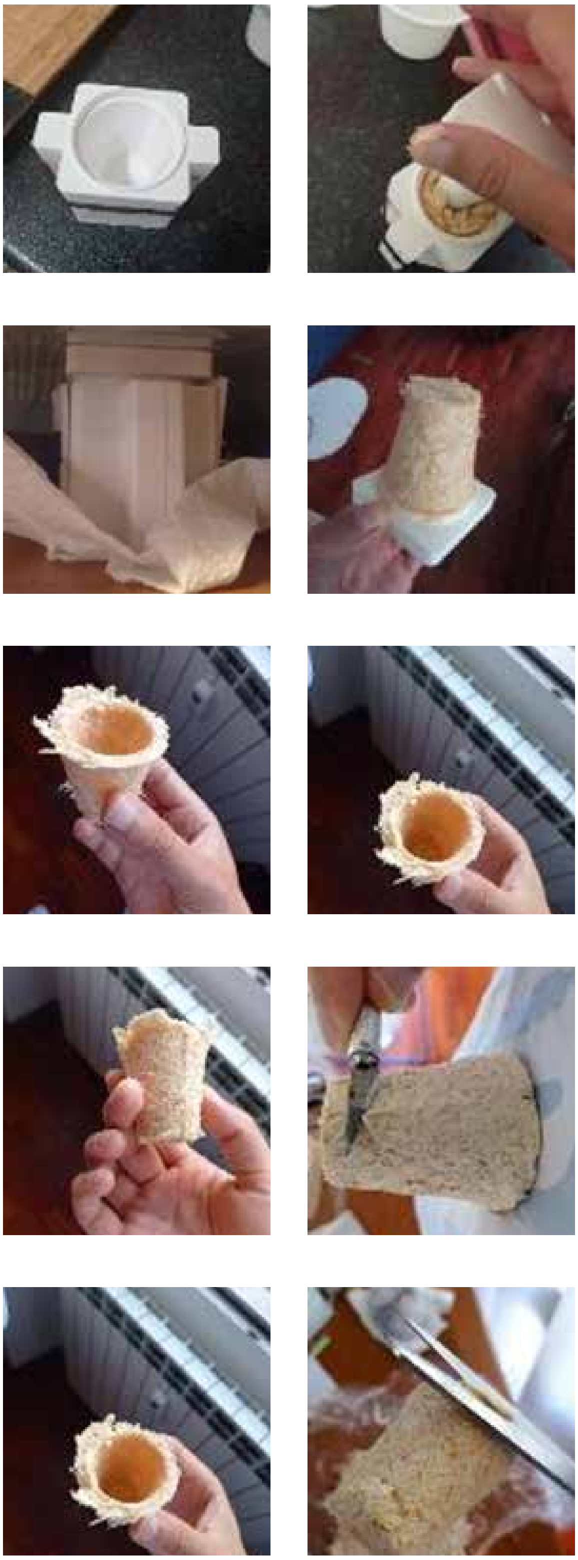


Figure 31. Replicating successful moulding process with corn starch + sawdust recipe for 3D printed moulded glass.

7.4 TOOLING DEVELOPMENT

Having already understood and proven how compression molding works for the production of biomaterial pieces, a tool to aid the experimentation could be developed. Different references from already existing pressing or clamping machines were analyzed in order to develop similar systems that could aid the molding process, while making it accessible to the user.

Initially a single prototyping tool was developed, but due to its size limitation, additional prototyping tools were made to broaden the possibilities and range of products to be made with this material. The main tool that will be described is the Compression Molding Machine, a machine that aids the prototyping of the sawdust-based biomaterial's compression molding through a clamp-lever mechanism.

7.4.1 References

The objective when developing a machine was to design a tool that could ease the compression molding process previously discussed. Ideally, it should be low-tech, meaning it should require mainly mechanical motion and operation, and affordable, since the users' context approach. Going through different references already existing, the brick making machine came as one of the simplest ways of generating pressure on a single object. They are used to generate bricks by compressing clay powder into two small containers, where a lever pivots and pushes a piston inside the powder container, while, at the same time, pushing down the lid that covers this container. The machine applies the main principle of torque force, where the pressure generated will be proportional to the length of the lever and the force the operator puts in, considering that the torque that can be applied depends 1) on the force being applied, and 2) the length of the rod being placed under stress $T=r \times F=r*F\sin(\Theta)$.

Figure 32.Torque force diagram (University of Guelph, 2022)

The machine itself is generated through steel metal sheet and can produce 2 bricks per operation, considered as: 1) adjusting the containing tray, 2) loading the material, 3) closing the lid, 4) lower the lever compressing the material, 5) open the lid and extract the brick. The machine has a system where different fittings can

Figure 33. (China Brick Machines, 2021) Brick machine production process. 1) Pouring brick powder 2) Placing brick powder on the compression compartment, 3) Pull lever to compress, 4) Pull out brick.

be placed in order to change the type of hole that will go on the brick. The outer shape will always be constraint by its rectangular fitting, but the inside will vary depending on the fitting shape.

The machine itself is generated through steel metal sheet and can produce 2 bricks per operation, considered as: 1) adjusting the containing tray, 2) loading the material, 3) closing the lid, 4) lower the lever compressing the material, 5) open the lid and extract the brick. The machine has a system where different fittings can be placed in order to change the type of hole that will go on the brick. The outer shape will always be constraint by its rectangular fitting, but the inside will vary depending on the fitting shape.

Figure 34.Brick maker showing hole casings (Exportsindia, 2020)

Different DIY approaches have been using a similar lever compression system in order to accomplish a similar task. From can compression, to hay block building, and to the same brick generation. A similar approach is the clay extruder, that uses a piston moving system, but instead the inclosing capsule is a cylinder, and it is usually used to extrude, not to compress. The benefit of the brick compressing machine is that it allows the piece to be extracted easily, it does not have to be taken out manually or with additional tools, but it is the same machine that extracts it. A different approach to extract the piece seen by the hay molder (Figure 35.3) is to create a door on the compression chamber that, once the piece is compressed, it can be opened to remove the piece from the machine. This has an additional use that allows to tie a knot around it to store it later. This particular solution restrains the amount of pressure that can be made on the piece since a wall container now has an opening and it is being held by a lock and a hinge, it is no longer a solid piece, therefore will not hold as strongly.

Figure 35.Clay extruder (Bailypottery, 2020), Wooden Cruncher (instructables, 2020) (Price & Ward, 2021)

7.4.2 Design procedure

Once defined the references the approach was to constrain the machine to a certain measure. In the case of this project, a reasonable measure would be the ones for the molds already developed, therefore 90 mm width x 90 mm length and around 70 mm depth. These constraints were used in order to start parametrizing the model; therefore, all the measure will derive from these initial ones.

The machine was developed in the Opendot laboratory, using the Shopbot CNC machine with a bed size of 2,50 x 1,50 m. For the resistance, ease of milling and availability, it was chosen to use plywood as the main material to work with. For example, due to the interlacing of the wood sheets it is composed of, it provides better resistance than a regular wood piece can give. Finally, the thickness of the plywood was decided to be 12 mm, since it was a measure still slim but sturdy enough to resist pressure load, other than being one of the standard measures in the market.

The piece was modeled in the CAD (Computer Aided Design) software Autodesk's Fusion 360®. A software that allows parametric modelling but that at the same time has embedded features designed for the manufacturing process or CAM (Computer Aided Manufacturing). This facilitates the process of going from design and modelling to manufacturing. The software was chosen for its parametric capabilities due to the flexibility it allows when changing or modifying certain parameters. Since the machine developed is a prototype, many changes will undergo its design, therefore being able to change a parameter and measures without the need to remodel the whole piece, is paramount for a quick and trustworthy workflow.

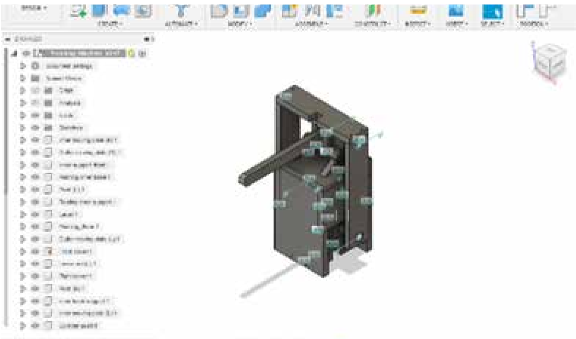


Figure 36. Assembled compression machine version 1 - Fusion 360

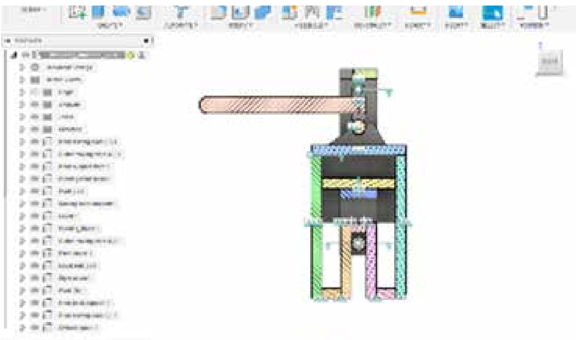


Figure 37. Section view to analyse the inside spacing of the assembled machine.

In this process, the pieces can be modelled in the same workspace. This is comfortable in the sense that, while modeling, the user can assure the fittings and spacing of the whole assembly. Once the pieces were modelled, they could be constrained in order to understand their movement, and to observe if the machine works accordingly. These constraints allow us to produce an animation of the complete model, understanding additionally the amount of space that will be available for the mold in the compression chamber or for the raw biomaterial mix. Moreover, it allows to see, when compressed, how much will be the distance of retraction, giving an estimate idea of how much the material will be compressed, and how much material is needed for certain kind of compression (light, dense, very dense, etc.).

7.4.3 Manufacturing process

After modelling and controlling the virtual assembly of the machine, it was ready to go into manufacturing preparation. For this a Manufacturing Model had to be created. This model allows the user to modify, organize and, in this case, arrange and nest the pieces of an assembly to prepare them for the manufacturing procedure. The software allows to arrange the pieces and optimizes them by inputting the stock (the material in which the product will be carved) and defining parameters such as the distance between pieces and how far away the pieces should stay from the borders. This facilitates the manufacturing process and optimizes the material, using the greater amount of stock possible.

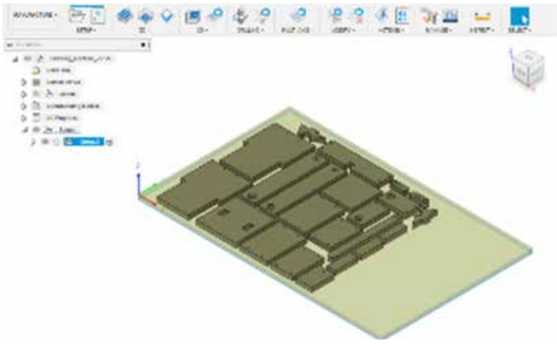


Figure 38. Nested parts of the Compression Moulding Machine inside the defined stock – Manufacturing model

In the milling process, for little pieces such as the Lever_Linkage, tabs were placed in order to avoid any slippage during the workflow. The tabs are bridges that the software places on the tool-path, that restrict the mill to completely cutting the contour of the piece allowing it to stay in its place. Later on, with a chisel or a little saw the tabs can be removed and then sanded to have the finished piece.

After the milling process is done, although the cutting procedure is very clean and leaves almost no rough edges, it is still important to sand the pieces to give them an even and smooth finish.

Once the pieces are completely sanded, the assembly process with screws begins. Following some of the principles already stated in the Circular Economy section, planning on the future disposal of the product, it is important to allow both easy assembly and disassembly, therefore restricting, if possible, the use of glue.

One of the pieces that can be particularly chal-

In order to follow the names of the parts of the machine, and go further into details please reffer to the technical information attached to this paper. (Technical drawings, bill of materials, assembly and/or manufacturing process).

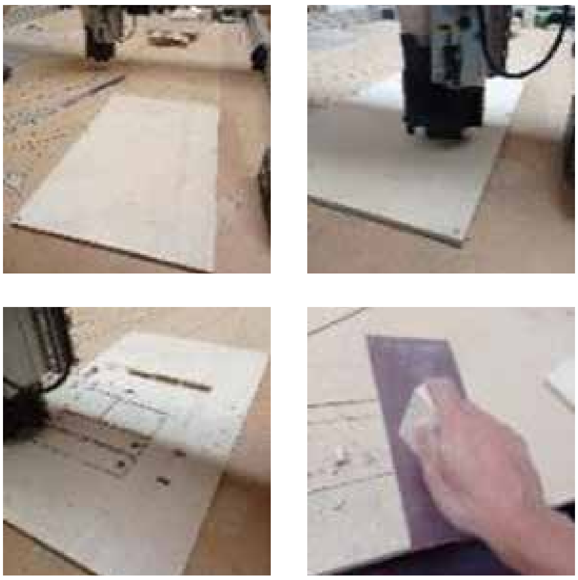


Figure 39. Milling and sanding process of the Compression Molding machine

lenging to manufacture is the Pivot_Ram, the piece which holds the lever in place in supported on the lid. To achieve the fittings for the linkage with the lever, the wood cylinder has to be cut, and then carved with a chisel in order to create the said openings.

Figure 41. Pivot_Ram carving process

Once all the pieces are milled, sanded and carved, the assembly is made either by glue (just for the Pivot_Ram), joints or bolts.

7.4.4 Initial prototyping and experimentation

Once finished the assembly of the machine, it was time to test it. For this initial prototype, since the piston that pressed outside the piece didn't go out enough, some help from a plastic film was needed in order to separate the pieces from the compression box. A recipe of corn starch, vinegar and sawdust was used to make different tests.

Some initial tests were made to develop simple bricks. Then a negative of a product, in this case a lip balm, that could be used as a packaging device.

It is important to notice that if using products as negatives for molds or packaging material, they should be completely covered, and should not show any undercuts, since then the piece will either break when pulling out or get stuck.

Since the initial bricks weren't compact enough, and the machine wasn't compressing completely as it should, in order to achieve more compres-

Figure 42. Process of recipe making and compression material with an inside shape - Packaging test

Figure 43. Additional compression experiment with cardboards to reduce space and increase density in the final piece, and sanding of final piece.

sion, a stack of cardboards was placed to reduce the space between the inner compression box so it would generate a more compact figure with less raw material. As stated, the block was well compacted but took an irregular shape due to the flexibility of the cardboard that was placed beneath it.

The resulting piece was a solid block, but still very light, resembling a piece of Styrofoam but sturdier. After some attempts to sand the piece, although it straightens, to a certain point the binder of the mixture starts avoiding sanding, so it starts sliding off the sandpaper, additionally the sanding paper starts tearing away some pieces of the block and chipping it away.

7.4.5 Machine adjustments

Although the machine was fulfilling its purpose, there were some adjustments that could be made to make it more flexible and increase its affordance. First of all, the height of the inner compression chamber could not be varied, therefore, how compressed the material would end would depend just on the type and amount of material the user is placing inside it. Secondly, while lowering the lever to compress the material, the user had to hold the machine with its other free hand, so the machine won't tip forward, making it harder to execute its function. And finally, when compressing the material, the Piston_Base didn't pull up high enough, so the user could easily extract the compressed piece.

For the initial problem, the height of the machine was increased by 15%, and different fittings for the pivot that hold the Piston (meaning the base which pulls up the material to compress it against the lid) could have different heights. Additionally, a holder with three different heights was designed so the Pivot_Ram, could vary the pressure applied on the product.

For the second issue, two supports were placed on the base of the machine, so it could easily be clamped to the edge of a table or to a clamp fitting. This change allows the user to use both hands, if needed, on the clamping procedure and do not worry about the machine tipping off.

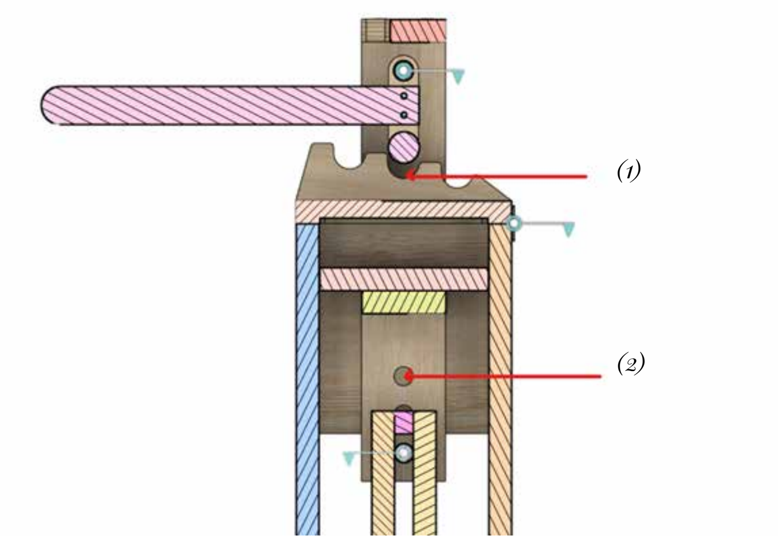


Figure 44. Machine adjustments (1) Pivot height adjustments (2) Piston height adjustments

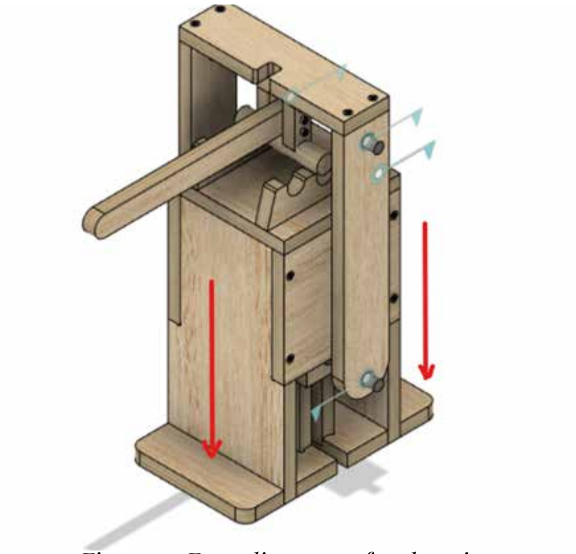


Figure 45. Feet adjustments for clamping

The inner height of the piston was increased so the material, once compressed, while opening the lid and pulling up the Piston, the material will spurge out so the user can extract it easily. Lastly a pocket designed to hold the upper mold

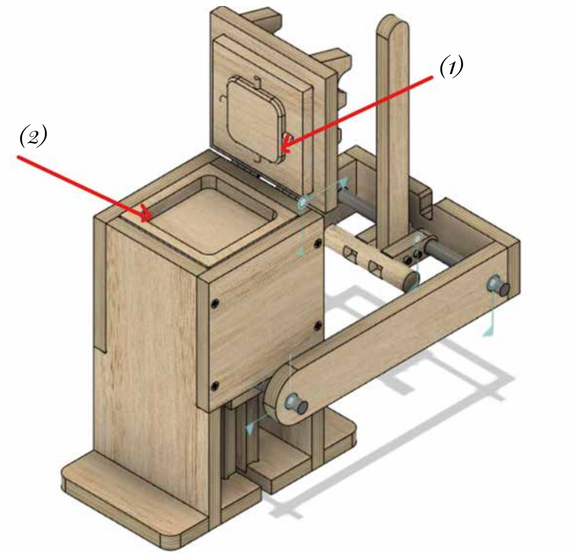


Figure 46. (1) Upper ashtray mold inserted in pocket lid (2) Protruding mold allowing easier extraction of the piece

face was included to facilitate the positioning of the mold, and the handling of the machine when having molds.

After the changes were tested on the CAD model, the same steps for the manufacturing process were modeled.

7.4.6 Mold manufacturing

Milling

Once the new version of the machine was defined, the next step was to start testing it. For this, an ashtray mold was designed and manufactured through milling, made out of MDF and plywood. The idea was to respect the proportions given by the machine developed, and test whether or not the fittings tested on the CAM will work on the manufactured piece, or not.
The mold was designed starting by the whole piece, meaning the ashtray was modelled first, and from it, through Boolean operations of subtraction, the two-part mold was carved out of the original piece. The upper part being the one that will press it's inside, and the bottom which has the bounding box for the piece.

Once milled the two pieces, the upper part was placed on the pocket lid, and the lower part over the piston. It is worth noting that to mill the lid of the machine, three milling processes had to be

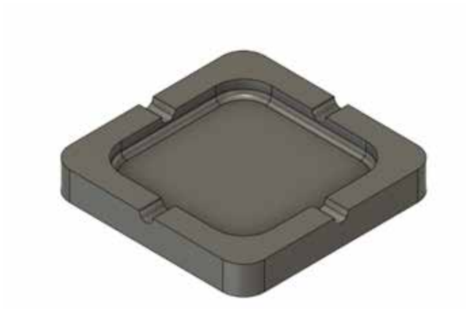


Image 39. Ashtray 3d model

made, two for the features of the lid, and another on a sacrificial board of the contour of the lid, so it functioned as a placeholder to work both sides of the piece.

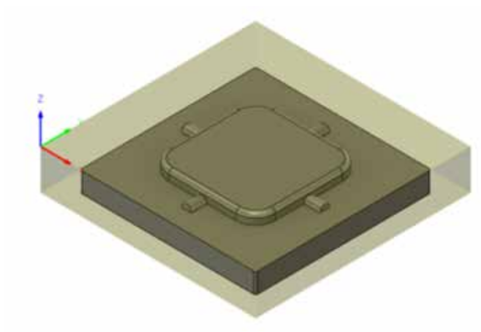


Image 40. Top ashtray-mold modelled piece

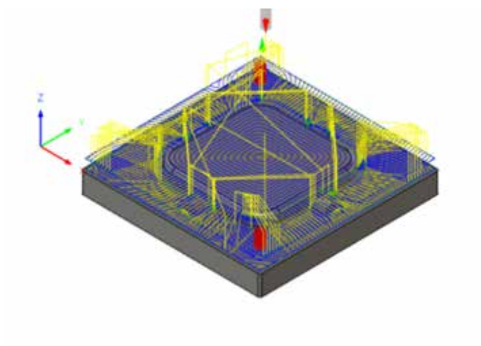


Image 41.Top ashtray-mold milling process.

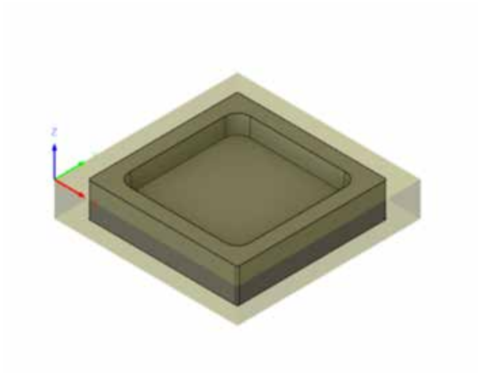


Image 42.Bottom ashtray-mold piece

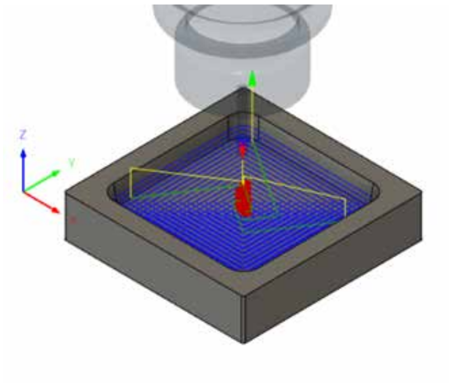


Image 43. Bottom ashtray-mold roughing milling process

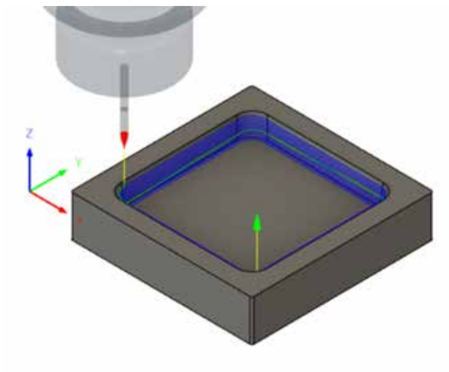


Image 44. Bottom ashtray-mold finishing milling process

The two mold pieces were varnished in order to avoid sticking of the material while pressing it and easing the extraction.

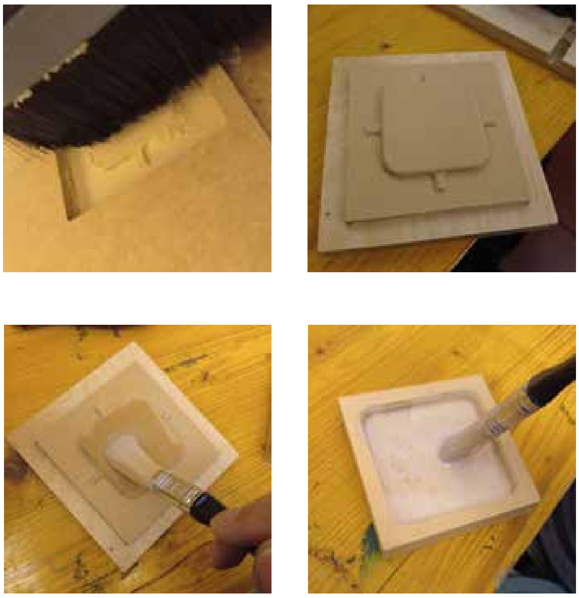


Image 45. Milling and varnishing of the ashtray two-faced mold

3D Printing

At the earlier steps of prototyping a 3D printing structure was well stablished for molding solid pieces. Although the initial idea to take off the bottom and top layers, leaving just the infill to allow the piece to dry while pressed didn't work, different molding strategies where stablished to facilitate the molding, and unmolding process (some of which are already stated in engineering literature).

The molds designed for cups, although they had an upper draft angle to allow to extract the piece from the top, were made from three pieces. This facilitates even more the extraction process of the piece. For these three-piece molds side guides and upper guides were placed in order to guide and align the mold when pressing it.

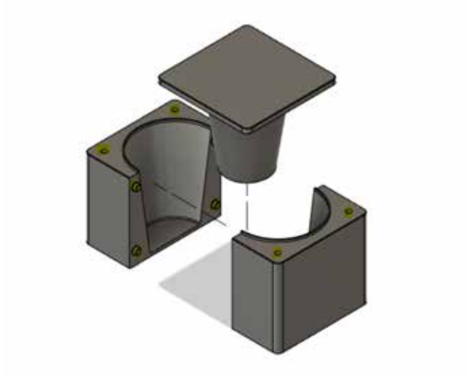


Image 46.Exploded view of cup mold

Mold exploded view, highlighting pin guides.

The process of extraction of the piece for this type of mold will be first the upper part, then open the two bottom parts.

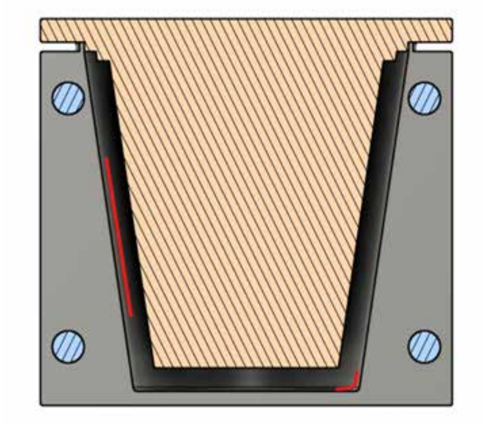


Image 47. Draft angles and rounded corners exemplification

Draft angles and fillets were considered to ease the extraction of the piece, being careful, when designing, to not leave any undercuts that might damage or obstruct the piece when unmolding. Now, since on the first molds there were being issues of material sporging out of the mold while pressing, that obstruct the closing of the mold, a cutter lip was designed in order to divide and cut this excess material.

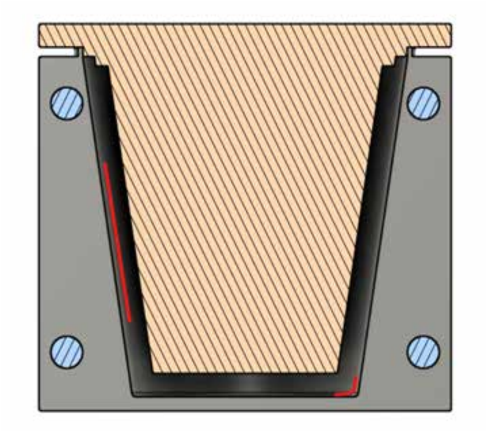


Image 48.Piston and cutting lip.

This cutting lip for this piece was modelled slimmest possible to allow cutting of the protruding material and high and enough to let space for it to come out, but not so slim and not so high so it would break while pressing the mold. This piece has the additional function of a piston container. For this a second part of the mold was designed with the function of a piston that will push down the material inside the mold. This part is tight with the cutter lip, so all the material that is inside should go into the filling of the piece. Since it was understood that the more dense and more compact the material is, the better these two pieces allow us to reach this goal.

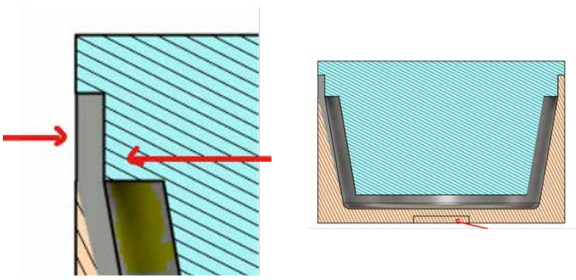


Image 49. Additional example of mold guides

There are different examples of how the guide alignment can be designed, same with the piston and lip cutter. Image 48 shows different examples of how they were approached.

3D Printed molds and the machines

The molds developed were designed with the machine in mind, considering its enclosing dimensions. As the machine has 70 mm of height limits the number of molds it can handle. This measure is enough if considered the final piece, but since the printed molds have additional offsets on top and bottom parts, the height of the final part hast to be much less.

Image 50. Mold not fitting in the machine.

Apart from this, different from the molding process designed for the machine, the 3D printed molds have an additional lid that adds an offset to the height that is needed to clamp down the piece.

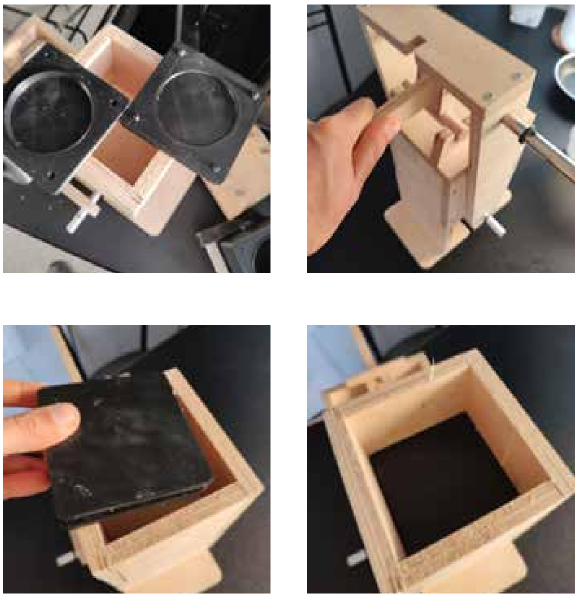


Image 51. Flat mold fitting on the machine. Compression not working completely

Now, when trying the machine with a much smaller piece, although it fit and the lid reached the piece to clamp it, since the plastic is rigid and the mold had a stopping point, the clamping mechanism of the machine is not able to reach the blocking points, therefore the machine doesn't clamp properly.
Although demotivating, this insight was important to understand the limitations of the machine, knowing that the molds that work are the ones designed to fit in their respective slots (e.g., ashtray mold).

7.4.7 Supporting tools

On addition to the machine and 3D printed mold, different tools were either obtained or developed to produce different objects.
Now, due to the limitations of size of the Compressing Machine, other tools to generate molding compression were developed.
Semi-fabricated objects are usually made in large formats, plywood, MDF, other particle boards, even beams, bars, tubes are developed in a format thought for industrial and mass production, this with the help of rolling or extrusion industrial machines. Although a big format prefabricated material due to their measures can't be done (usually between 120*240 cm of area for particle boards and 2-6m length for beams) and will also be unpractical, a scale press was ideated to replicate a similar product.

A press mold for a 35*35 cm sheet was designed. Since the pressing mechanism would have been overly dimensioned for the product, a press to be pushed through clamps was thought. Initially, the press was thought of as a mold with a piston and a blocking mechanism to control the thickness of the product, but later it was seen unpractical, because it would have limited it to just one height. Instead of this, a piston that could go completely in the mold was thought where the height of the piece will be defined by stopping blocks that can be placed inside the mold cavity. Again, this piece was modeled and designed so it could be milled here through Fusion 360, the piece was modeled and then prepared for manufacturing.

The piece consists of 4 parts: the piston, the base, the containing frame and the extraction

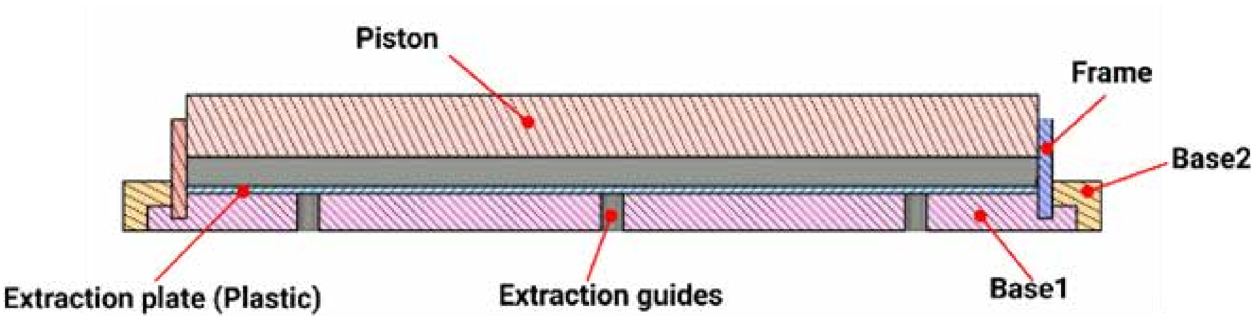


Image 52. Section view of the sheet compression molding machine

plate. The piston consists of a 35 x 35 x 2.5 cm plywood block that has a handle in order to press and later extract the part, when the piece has been pressed.

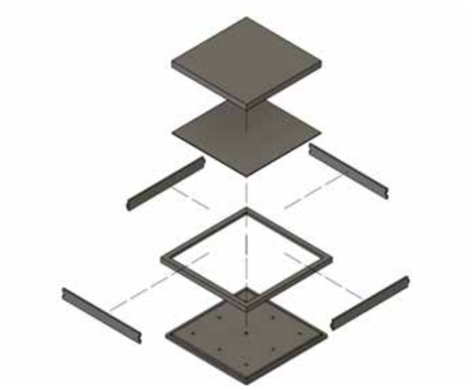


Image 53. Exploded sheet compression mold

The base is assembled in 3 parts. The inner support (Base 1) and the outer frame (Base 2) are used to contain the frame of the mold. Although this piece could be carved from just one wood piece, dividing it allows to save more material, and to have a modular mold, where the containing frame does not depend on the thickness of the plywood. The third part of the base is a 3 mm MDF plate (Extraction plate) that is placed in the base of the mold. This plaque will be used to extract the piece by pushing 8 mm dowels through the inner support holes, where the platform can be pushed pulling out the piece without deforming it or even breaking it.

Image 54. Milling of base 1, Milling of containing frame, Assembled base, Holes for piston assembled

The containing frame consists of four 34.8 x 4 x 0.6 cm birch plywood pieces that intersect between each other in a horizontal way, creating a rectangular frame which will contain the molded and pressed piece.

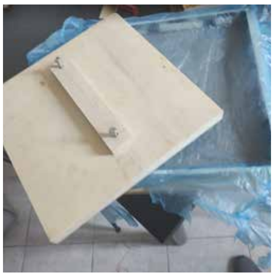


Image 55.Complete sheet compressing mold, Pressed sheet compression mold.

Finally, the mold is pressed placing from two to four clamps on each of its corners to obtain a uniform pressing. Once again, 4 stoper pieces of the measure of the desired final thickness of the piece are placed in each of the corners if wanted a specific thickness.

Image 56. (1) Used pot, (2) Compressed used pot

Lastly, as an alternative tool for compression molding pieces, a used cooking pot was used. For this only a circular plywood piece was milled in order to fit the opening of the pot, and fit tight for the compression of the material. Once again, the piece is pressed with the help of clamps. For this mechanism a marking system on the side of the pot is used to arrive to the desired thickness of the piece.

The advantage of these two molds is that they are resistant enough to place them inside the oven, adding heat to the process while pressing.

7.5 PRODUCT DEVELOPMENT

Image 57. Prototype product base of sawdust biomaterial

7.5.1 Material overview

Once having a solid material base and a process with which solid pieces can be manufactured, product development was the next step to truly test the viability and functionality of the same.

From the different tests made an aesthetic and qualitative characterization of the material was done. Although the material texture and rigidity vary depending on the type of sawdust being used, a general characterization, taking the common points present in each material was considered.

The first process was to characterize the type of sawdust that could be obtained:

Image 58.Fine – milling, sanding, sawing.

Image 59. Mid-size – brushing, cutting, turning (mixed fine + fibrous).

Image 60. Fibrous – sawmill, turning, brushing.

The characteristics depending on the type of sawdust vary in the following way:

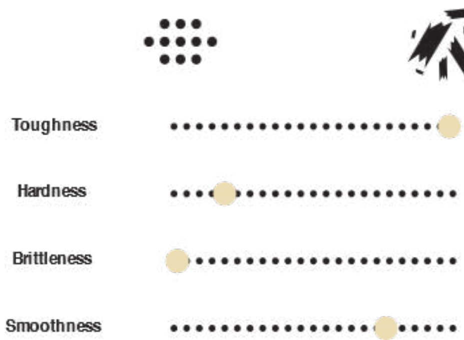


Figure 47.Change of properties of material due to type of sawdust in the mix

As seen, depending on how the sawdust is mixed the material's properties vary, meaning that for more resistant but softer material, long fibrous sawdust is used. While if hardness (compromising brittleness) is needed, a particle sawdust should be used. Of course, to reach a mid-point, both can be mixed in order to modify the properties inside the limit ranges.

The next chart shows an overall behavior of the material (considering the different types of sawdust).

Figure 48. Property characterization for biomaterial proposed

As seen, the material is defined as rough but strong once dry. As its matrix base is sawdust, many of the wood properties transfer to the same: therefore, works as thermic isolator, can be sanded, milled, drilled and sawed. The manual working of the material works more when the sawdust used is grainy, meaning the particles that hold together the material can be removed and be worked more easily. On the other hand, when using fibrous sawdust, the intertwining of fibers makes it hard to separate. Additionally, the binding of corn starch recipe generates a polymer, hence making the removal of sanding harder. As it polymerizes, a bioplastic filament protects part of the matrix from being worked and sanded. Once again, this happens mostly with fiber sawdust.

Continuing, laying down the qualitative properties of the material seen, a way to test these is needed. The most interesting properties to examine via products *were texture, strength, thermal and sound isolation:*

Texture was thought as an interesting property to test, exploring the decorative aspect it has, showing a very natural and rough finish with products reaching a similar appearance to cork, or compensated panels. This gives a rough but classy look, exploiting the idea of a sustainable product.

For the *strength*, seeing how the small products end up rock-like, and very stiff, the idea of using this for a bigger product was ideal to test on a bigger scale the material. Products such as shelves, stools, or tables were considered in order to test the material.

The *thermal property* was considered since it differentiates the product from other biomaterials and is interesting to showcase how similar wood properties are transferred to it. For this, products that interact with heat such as lamps, hot pots, cooking items, were taken into consideration.

Lastly the *sound absorbent or isolating property* was chosen mainly due to wood's properties. This material, other than thermal insulator, can be phone absorbent due to its porosity. Now, converting it into a biomaterial increases its porosity, and reduces its density, meaning it has the structure to attenuate sound waves. Although the effectiveness of the product cannot be scientifically tested, a formal approach can be defined.

7.5.2 Texture

As the initial test of texture, the ashtray mold was mold and compressed. This product gave the idea on how, once dried the piece, the texture of the product was very rough and had a corklike feeling.

The piece was molded with the compression molding machine, with the help of a bag to be able to extract the piece.

As seen in the pictures the piece was mold successfully, although having some excess on its sides. The piece once compressed and taken out, was left on top of a radiator which increased the speed of the drying process. Once the piece was dry it was sanded and polished to reach the final result.

The decorative products such as the ashtray were an interesting group due to the amount

Image 61.Pressing, drying and sanding of the ashtray piece prototype.

of plastic experimentation that can be done with them seen from the reference of Ricardo Cenedella (Cenedella, 2023), where plastic experimentation with sculpting gave an interest set of table ware.

A same formal experimentation was made for a bowl, where a long fiber was placed inside an already existing molded bowl, with aluminum foil. This foil allows for easier extraction.

Image 62. Bowl sculpting with aluminium foil for easy extraction

The material was placed in the inside of the bowl, knowing, from the experimentation process, that if placed on the outside due to the shrinking it could break.

Image 63. Dried bowl taking off aluminium foil to complete the other half.

Once semi-dry on the inner part the aluminum foil was taken off, so the complete bowl could dry without any problem. Again, taking what was observed from the experimentaiton, the bowl was selected to be made with fibrous sawdust because it will hold better the structure, ressist more the tension of a process that doesn't include compression molding.

7.5.3 Thermal Isolation

A thermal insulator was planned as a prototype to test the thermal isolation properties of the material, but instead practical tests were made in order to see how the piece burnt and how it transferred heat.

Image 64. Thermal insulator cup drying and mold extraction.

The idea was to create two cups with lids, that could hold a cup of coffee inside them, one made out of biomaterial and the second one of plastic. The experiment consisted of placing the coffee cup with hot water at the same temperature, and closing each of the cups, measuring the temperature at the beginning and at the end of the same. The difference of heat loss would have given the container that had better insulating properties.

Due to the fact that making the insulator was not quick or easy, the experiment got discard to try a more simple and straight forward approach. Although a different approach was taken, the molded cup was still used as a prototype to understand better the limitations, and the processes to mold the material for bigger pieces.

Image 65. Insulator cup sanding process

Image 66. Insulator cup after sanding

Furthermore, two pieces from the same material were laser tested with both cut, raster and vector engraving, having optimal results. As already discussed, the material, in this case, replicated the property of the wood in the sense that is a material that allows it to be lasered.

Image 67. Lasering tests with the sawdust biomaterial

Image 68. Lasered sample 1 - Burned on the cut test

Image 69. Lasered sample 2, clean cut, raster and vector engraving

As seen in the pictures, eventhough the material has a bio-plastic mixture inside it, is able to replicate almost perfectly the easiness of laserablility that an MDF, or raw piece of wood have. To reach this result, the piece has to be thoroughly sanded first though.

Image 70. Pressing, drying and sanding of the ashtray piece prototype.

Continuing with the isolation test, it was thought that simply doing a burning test of the piece will give us enough insight to understand the thermal properties of the material. As seen in the different pictures, the piece burned without transmitting heat to the fingers that were holding it. This simple test allowed us to understand the properties of the material and continue to propose a product that could profit from it.

Image 71. Cork wood working products by Melanie Abrantes

Considering the reference from cork like products, or thermal isolating products, it was decided to produce a cup holder. A holder made out of biomaterial, that will hold a cup that usually will have in it hot water. This holder will act as insulator, avoid the heat to transfer from the hot cup to the hand of the user.

For this piece the 3D molding strategy was used.

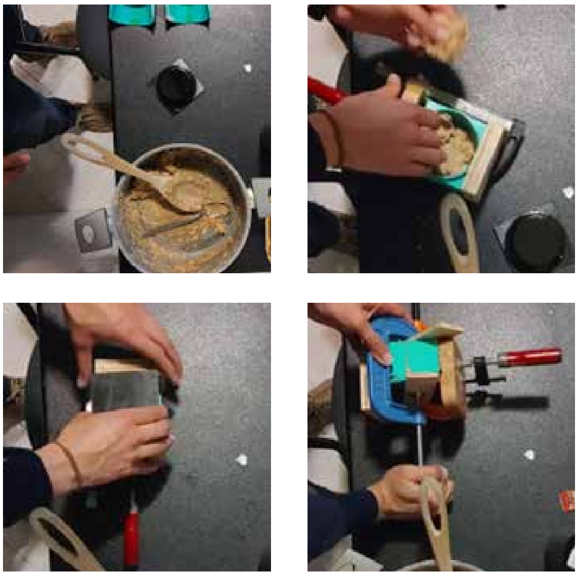


Image 72.Mold pressing of teacup holder.

Due to different failed attemps of doing the mold with fibrous sawdus, it was attempted doing the mix with a combination of two different types of sawdusts, particulated and fibrous.

The problem of the initial pieces were mold related but also visosity related. The fibrous mixture has a harder time when compressing the mold to reach all the parts, so an initial homogeneus spread of material around the mold has to be done, in order for it to reach all the cavities inside the mold.

A 3D printing glass, simulating the cup was made in order to complete the prototype.

Image 73. Dried and assembled teacup

7.5.4 Sound isolation

It is known how wood has the property to mitigate or dissipate sound waves due to its porosity. In fact, wood is usually used into the construction of isolation booths, music cabins or even theatres. As demonstrated by the authors in the article Sound absorption of wood-based materials, for frequencies between 125 and 500 Hz, the highest capability of sound absorption was determined of low surface layer density and high porosity (Jerzy Smardzewski, 2015). All of these are characteristics that have been already proved for the material, hence the chance to propose a product that exploits these properties. For this product the sheet compressing mold was used. Since the objective of the panel was to be strong to hold together, a mixture between fibrous sawdust and particulates one (50-50) was made. The piece although thoroughly compressed, due to wrong calculations, didn't fill completely the mold. After leaving pressed the material for a day when taken out it was placed on the oven to speed up its drying process. Since ovens heat but don't extract the humidity out of the enclosing box, the process is still slow. Various series of drying through then drying on the outside had to be done to have a completely dry piece. This whole process took around 4 days.

Image 74. Compression and drying of biomaterial sheet.

Once dried, it was obtained a sheet of around 6 mm thickness which was hard as a rock. The combination of the types of sawdust worked as expected considering the part was hardened but the brittleness was counteracted with the fibres of the second type of sawdust.

Image 75. Dried biomaterial sheet.

This plaque was possible to receive a sanding procedure and later cut with the band saw. The material holds perfectly these processes allowing us to reach a hexagonal panel. Initially it was considered the possibility to mill the top part to reach create a pattern suited for phone absorbing, but due to the same natural texture that had the material, it already generated bump patterns that worked as such.

Although the result is interesting, the material was very stiff and rigid for a phone absorbing panel. This was due to the mixture of sawdust used (particle and fibre), since it hardens the final sample, making allowing it to be denser and more compact, also due to the compression moulding process.

Image 76. Sanding sawing and finished look of biomaterial panel.

It was already seen how the fibre sawdust only mix, was softer, and more porous than just the particulate one, or the one mixed, since the fibres' length allow more empty spaces inside the material, making it less dense. Although the pattern obtained on the previous object was textured and interesting, a more conscious choice for the next one was made.

When talking about dissipating a sound, it being a wave, when it is emitted and bounces within a certain object, it loses energy therefore the more it bounces the greater the energy loss or dissipated in this case. Considering this if a sound bounces against a straight wall in an empty room the interference is minimum, but instead it the wall is corrugated and the room full of objects, the sound will be more obstructed and therefore more dissipated. Having the later in mind, corrugated or irregular objects give the sound more surface to bounce off, instead of having a flat one: the more irregular the surface the better.

Since parametric modelling has been a recurrent theme during this project, we didn't make an exception for this product. A sinusoidal pattern was parametrized to mill it in an already existing biomaterial panel.

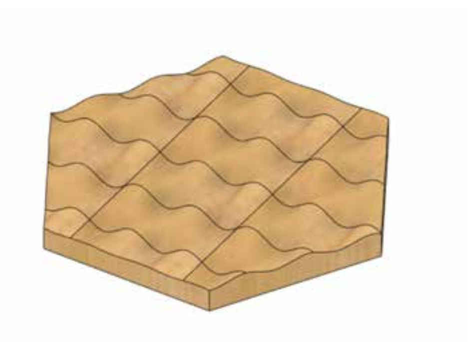


Image 77. Sinusoidal phone absorbent panel

A sine function was developed in order to control the waves seen on the panel, this makes tweaking and tinkering much easier since by changing two parameters the pattern can be adjusted regarding the aesthetic searched for. A wavelength and pick height were chosen of 80 and 12 mm respectively.

The panel comes out from the stock of a 24 mm biomaterial piece, that through a milling process will be carved and cut.

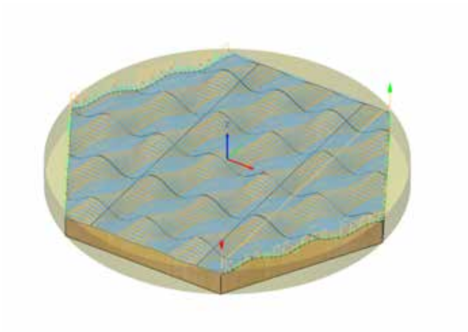


Image 78. Sound absorbent panel – manufacturing

The hexagonal shape was chosen for its modularity, searching a beehive organization which allows to better stack the panels on a wall once finished.

Image 79. Panel hanging system.

Due to the type of material, the easiest way to hang them is with picture hooks. It is a standard component that can be easily found. Now, even though the material is porous is dense enough to hold tightly the screws placed.

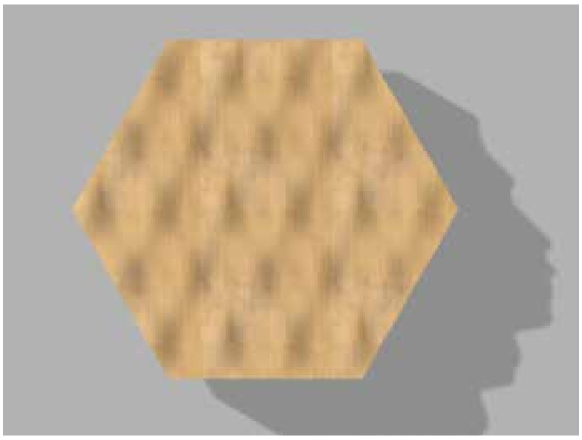


Image 80. Render of bio-sound dissipation panel

7.5.5 Toughness

Lastly, to test the toughness of the material the selected product was a stool. A seating stool is the ideal product to test if a piece made from the biomaterial can withstand the weight of a sitting person, and maybe, why not, of a standing one.
An initial process to produce the stool was developed. The first idea was to use a used cooking pot as the mold of the stool seat, while embedding the legs in the whole mix to end with a complete product at the end of the cooking mixing

Image 81. Initial stool prototype 3D model concept

Image 82. Stool version 1: 3D model and legs

Three legs with two dowels each were designed so the legs could grip when the mix of the stool's seat has been already dried and cook. The idea of this whole montage was to insert it pressed

Image 83. Oiled pot for moulding

As a preparation, olive oil was placed on the bottom of the pot to later extract easier the piece. Additionally, the piston of the assembly was wrapped in aluminium foil and then washed in olive oil to achieve the same result for this part.

Image 84. Foiled and oiled piston

Image 85. Seat stool biomaterial preparation where everything is mixed and then heated.

The steps for this recipe were slightly changed. Initially the bioplastic mix was being heated prior to introducing the matrix. For this piece, due to its size the whole mix was integrated together. It is known that the process of gelatinization of corn-starch starts within the 70º and 90º degrees Celsius (Bin, et al., 2021). Therefore, even though it will not be pre-heated, while cooking the temperature of the oven was placed on 80 so it could maintain the temperature and allow the mixture to bind and reach its polymerization process.

The mix was poured on the bottom of the pot, which will use as the seat, then the legs were embedded while later placing the piston to compress the whole mix. Once clamped, the montage was placed inside the oven.

After four hours, the mold was taken out. The

Image 86. Embedding of legs and cooking of biomaterial seat stool

seat piece was attempted to being taken out while standing up, and giving taps to its top but it didn't come out. A second try by pulling gently the legs. Even though the caution for the extraction, the piece broke and the legs were not even close to holding the legs.

The final mix was not completely dry, and felt cake-like, meaning it was grainy and soft. It is assumed that, in this case the process of polymerization took slower due to the interference of

Image 87. Result of first stool prototype

the matrix on the mix avoiding a uniform heat distribution. This might cause that some parts heat quicker than others, making the stool seat solidify in chunks.

Although this test did not come out good, a piece from the failed experiment was saved and left drying as if it was the final piece.

Image 88. Remaining dried and worked part first stool prototype

The piece was sanded and cut, ending up with a clean sample. As seen in the image, the compressed section view gives a resemblance to MDF. Structurally, the piece is very hard, and could actually withstand the pressure of a hand clamp compression. From the piece it can be seen as a usual problem when using mixed sawdust, which is mold proliferation. As already discussed, vinegar should decrease the appearance of it, but it is not always the case.

Now, for the second test, a simpler approach was taken. In order to manipulate easier, the mixture, it was decided to produce the seat, and then the structure to hold it.

Figure 49. (1) Minimal stool created by Berlin-based designer Hayo Gebauer (Hayo Gebauer), (2) Stools with bill textile (Mathis)

The structure had to be sturdy enough to give support to the material and at the same time allow it to show.

The seat Trig, by Hayo Gebauer gives a sense of support to the seat that distributes the weight of the person more on the legs than in the actual seat. For the biomaterial stool, this will allow to protect and prolong its use life. On the other hand, a stool that is able to showcase the material where it has more a function inside the cushioning, than structural, such as the reference by Angela Mathis, where she showcases pressed obsolete bills as the cushions of different stools, was taken also into account.

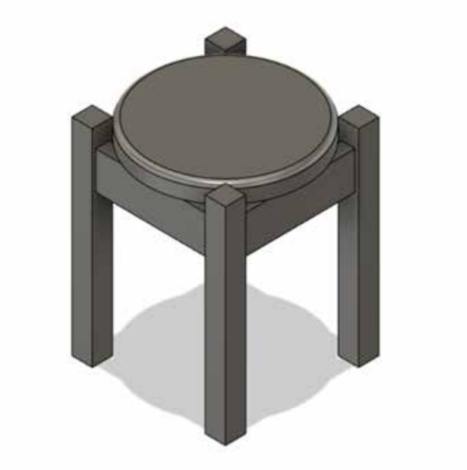


Image 89. 3D visualization of Stool version 2

Lastly, a model that could integrate the two ideas, but also be easily manufacturable was selected as an option for the stool.

For this prototype the same pot mold was used, and the dimensions of the stool were based on the pot measures. In this case a pot diameter of 23 cm and 30 cm in height. The stool was thought to be small for practicality, though the main user per definition will be children. With this, standard heights for stools were taken into account for their final measures (usually between 23.4 and 28.8 cm), rounding it to 30 cm as a final height. Even though the stool would be small, it had to be sturdy. Different from the first recipe, here it was used fiber sawdust in order to facilitate the binding process of the mix.

Image 90. Pressing and extraction of Stool's version 2 seat

The same process of mixing the ingredients and then heating them up was used. In this case, the mix was heated up in a stove while constantly mixing. This would allow the mix to heat uniformly and control that the corn starch reaches its polymerization point for all the mixture. Although this is a time-consuming process, it was found as the better way to assure the homogeneity of the mix, and its gelling process.

The mixture once heated up was placed on the pot, clamped and left for a day to sit. Once the day had passed it was taken out and placed on

Image 91. Drying process

the oven to accelerate the drying procedure. Equally as the phone absorbent plaque, the seat stool had to pass through different drying sessions of oven and natural drying.

Once dry, the seat was hard and sturdy enough to be picked up, moved around and pressure it with out It deforming or breaking. Now, due to the type of filler it had, some wood chips fell off now and then from it. This was solved with a sanding pass.

For the structure support of the stool a 20 x 55 mm pine wood beam was selected, then for the legs a 30 x 30 mm one. The structure had to be done off natural wood to accomplish its biodegradability, disposability and circular strategy (Design for resource conservation).

The assemby for the legs and the support was made through a wood joining fixture of wooden dowels of 6 mm diameter and 20 mm long.

Image 92. Cutting legs to measure, sanding pieces and opening dowel holes.

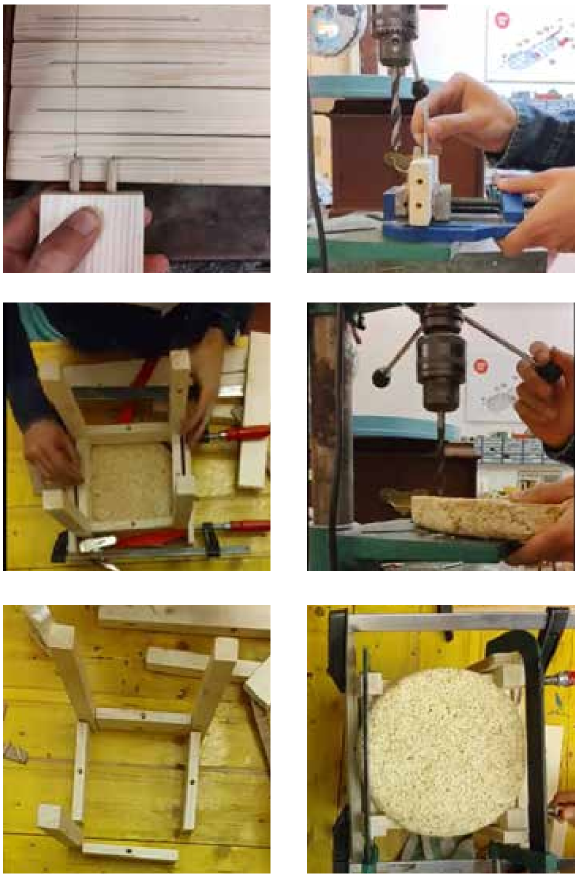


Image 93. Clamping, joining and pre-drilling to assemble whole stool.

Before joining the piece completely a pre-assembly of the structure was made in order to: 1) understand the position in which the legs and supports fit better, 2) mark the point where the seat will be drilled, and 3) control the structure could be assembled. Once this points where tested, the structure was fixed through glue and dowels, finishing compressing with clamps and straps.

Image 93. Clamping, joining and pre-drilling to assemble whole stool.

While the structure was attached through dowels, the joining of the seat to the support was made through screws. At the beginning, it was intended to place wood inserts inside the seat, so socket head screws could be used for the joining, but when screwing the inserts the biomaterial was not hard enough to keep them straight, therefore very hard to adjust the seat with the hole outlets. Finally the joining was made using M6 45 mm screws, and worked perfectly.

When the stool was finished an overall check was made. By holding it upside down, from the seat, sitting and evening doing hard pressure on it, both the structure and the seat holded well enough.

Image 95. Function and resistance test of finished stool

A third concept for the stool was developed to give more visibility to the biomaterial-made seat and have a deeper understanding on the material's behaviour. The inspiration was taken from a table developed by ODESD2, an ukranian interior designing company which rendered half joint plywood-legged tables:

Image 96. Plywood-half jointed tables (ODESD2, 2022)

Image 97. 3D model proposal of stool version 3

Due to the rigidity of the seat obtained, a milling process was proposed in order to straighten the lower part of the seat and make it fit with the legs. These are embedded with a half way joint, and have an upper cross that will go inside the seat which will be glued to the piece. Additionally four passing screws will attach the seat with the leg structure in the way shown in the section picture.

This structure came from an idea of still giving support to the seat, elongating the lower shoulders of the legs so they can support thoroughly the seat, but at the same time, reducing its visibility giving more protagonism to the bio-fabricated piece.

CHAPTER
EIGHT

Results

The following chapter will summarize and discuss the different results obtained in order to collect the different findings through the experimentation and product development process.

Image 98. Comparison between first sculpting test, vs compression moulding

After the manufacturing experimentation it was clearly defined the difference between molding and compression molding. These two pictures compare the before and after of applying the compression molding technique and the results obtained. Although the first sample can work as a different aesthetic, when searching for functionality and cleanliness, the compression molding es the option to go to.

Image 99. Glass compression moulding prototype

The following iteration of the cup, showcased better the possibilities of this technique, reaching to somehow more complex figures, with satisfactory results.

Image 99. Glass compression moulding prototype

The machine enhanced the prototyping process opening different ways of exploring the biomaterial

Once defined the compression molding technique a tool able to facilitate this process was developed. The tool as an aid for pressing the material functioned just fine. It did what is supposed to and aided the compression molding process without the need of clamps or additional implements to reach the desired result. Although the machine worked, the dimensions and operability of the same limited the product development process. This machine was able to prototype and produce different possibilities with the material within its dimensions.

Long fibre sawdust, allows space in between the bonds of the biomaterial, making it lighter and morbid, optimal for packaging solutions.

The machine allowed us to experiment with different blocked shapes, types of pressure, reaching somehow different results. It also allowed us to experiment with enclosing of products, approaching a packaging direction option that needs to be further explored.

Image 101. Styrofoam-like packaging block made with compression moulding machine.

Image 102. (1) Isolator cup with particle sawdust compression moulded.(2) Evolution of cups samples and tests until the end result

Particle sawdust works better for precission molding, allowing the mixture to flow more easily through the cavities of the mold

Entering product development, the cup was one of the first real scale models developed. Here some new challenges started appearing since the proportions, quantity of material and time of drying changed considerably between prototypes and 1:1 scale model. The product was developed with grain sawdust, altering the way the initial glass prototype was made. Although the purpose of the glass was experimental the results are satisfactory since it was a workable piece, meaning it could be sanded and retouched, it could be fixed when broken and at the end, hold the shape that was intended to.

Leaving the material take its own shape while sculpting it, without triming it or cleaning it, heightens its properties - *texture, curves, bumps*- therefore its beauty

For the sculpted bowl a formal experimentation process was re-adopted showing how compression molding is not the only process with which a product with this material can be manufactured. Instead, it showed the easiness of how we can reach a functional piece through hand sculpting arriving at an interesting organic shape that enhances and complements the look of the material, since it is in line with a natural and organic concept.

Image 103. (1) Bowl isometric view, (2) Top view (3) section of showcasing texture

Image 104. (1) Teacup assembled, (2) disassembled, (3-4) different cupholder tests

To profit from the concept and the material, as a future development the cup should be made out of glass or thin clay, whereas these are not completely isolating, but quite aesthetic, the two materials can work together harmonically.

The isolation teacup was an interesting experiment where the idea was to explore the thermal isolation properties of the material. Once finished the product it was tested with a hot tea. It was very interesting how the material truly isolated the heat expelling from the cup, allowing the user to take the cup without feeling the heat trespassing. Now, the only issue with this test was that, due to the low fusion temperature of the PLA, with which was printed the glass, it started melting and we were not able to finish the test, nor the tea.

The finer the sawdust the easier it becomes to work the piec, but at the same time the more fragile and brittle it becomes.

Even though the machine limited product development due to its measures, the way of using the molds to produce products worked perfectly. The ashtray/coin holder was an example of this. Although the final result was quite small, again due to the machine dimensions, it allowed us to show-case the idea behind the same not only for prototyping but also for product development. The ashtray piece, made of a particle sawdust, was one of the first samples that proved the properties of granular matrixes, showing it easiness when working, sanding and cutting.

Image 105. Mold compressed ashtray/coin holder

Image 106. Biomaterial hexagonal panel (1) Side A (2) Side B

With this piece we aimed to understand the mouldability process in a big format (35 x 35 cm) and the challenges behind it, being one the mixing of the recipe and second its drying time.

The panel showcased a resistance property of the material challenging processes such as orbital sanding and cutting through band saw. The panel was projected as a thermal sound isolating piece, but its test cannot really be done with just one of them. As for the material itself and the experiments developed, we were able to understand how some of the properties of wood can translate to the biomaterial itself. Something that can be seen in the picture is the difference in the finishing of both sides of the panel, side A was the one who was face down while drying, while side B face up. This showcase the moisture that the material is able to retain and how it is shown in the aesthetic of the final product.

The stool showcases the potential of the material through both a structural and aesthetic way.

As stated in the product development section, the stool's main purpose was to showcase the resistnace and strength of the material on a big scale and real life product. Through crash and usability testing it was seen how the material can trully ressist a normal handle within the context of a stool. Although no finishing was placed on the seat, it should be controlled how much the material by itself can be kept clean and protected. Already stated, the biofilm, generates a polymeric protection that allows the seat to be more ressistant than raw wood, but the observations have to be done through a longer period of time.

Image 107. (1) (3) Biomaterial seats (1 of fibre sawdust, 2 mixed powder and fibre sawdust) Version 2 Biomaterial Stool

CHAPTER
NINE

Conclusions

Throughout the document it has been pinpointed how the compression molding process was useful for the development of solid products with biomaterials. Going from a sheet like production, to a 3D solid piece was thanks to the forementioned process. Through the research part to the product development, biomaterials have an ongoing and evolving challenge. From the research point of view, it is understood the importance and ever-growing community regarding biomaterials due to the importance of the topic and what it represents: part of the solution to world pollution and contamination.

During the experimentation process there were understood the limitations and difficulties of biomaterials. First of all, it was seen how the recipes could change regarding the environment, whether it's wet, cold, humid, or hot it will affect different steps of the process, from the mixing, pouring and time of drying. It is very interesting, but at the same time off-putting, how a same recipe can have totally different outcomes at different times of the year. Secondly, it was understood that the DIY developing of biomaterials is an art, or better a chemical art, just as cooking or painting. It is a process that with slight changes can have different outcomes, the time the mix is left in the oven, the way the parts are mixed, meaning that although precision is required the ability to navigate through the changes of each production is also a must.

Taking from what was said in the previous paragraph, the material developed has a lot more opportunities to still be explored due to the ability to drastically change the outcome of the product by tweaking any part of the recipe or manufacturing process. From varying the proportions on the mixture, to the tools used to handle the material, to the different combinations either in the matrix, in the polymeric or plasticizer base. From this, although the variations are infinite, it is important to understand how the endless variations can be accomplished. Understanding the basic structure of how the biomaterials/biopolymers worked allowed us to propose changes over already established recipes that benefited the outcome that was being looked for. From the project developed it was seen how digital manufacturing is a tool that can be exploited through experimentation. Digital fabrication allows the researcher not only to rapid prototype, in this case with molds or tools, but it also closes the gap between the design spectrum, that when left in a concept can be speculative, and when placed just on blueprints lacks innovation. By joining and closing together these two elements, the possibility of having a well-designed and functional final product is much quicker and more reliable.

Even though during the project different matrixes for the biomaterial recipes were tested, sawdust came in not only because of the versatility it had, but due to its availability. Working at a fabrication laboratory, or a woodworking shop, sawdust is always available and usually a by-product that is wasted (mainly for small woodworking shops). As seen in different studies, the demand for wood, and its derivates is nowhere near slowing down. With wood, hence, sawdust being such a praised material, is paramount to understand their implications, environmentally and economically, not only at its raw state but at all parts of its value (or cascading) chain.

The products made with this material have the potential to generate awareness among the buyer on the different ways wood is either used, wasted, burned or overused. Even though it seems trivial, the material has layers and layers of complexity, both from the chemical and structural point of view, to the social, economic and political. This biomaterial is not only an opportunity to create a new product, but one for people to see its potential value outer and other than from its already known harmful uses.

Bibliography

3D Potter. (2022, 8 26). 3dpotter. Retrieved from 3dpotter: https://3dpotter.com/printers/potter-bot-10-super

Aboca. (2022, 11). Aboca. Retrieved from Aboca: https://www.aboca.com/company/
Aboca. (n.d.). Aboca.

Adidas. (2019). adidas.com/futurecraft. Retrieved from adidas.com/futurecraft: https://news.adidas.com/running/adidas-unlocks-a-circular-future-for-sports-with-futurecraft.loop--a-performance-running-shoe-made-t/s/c2c22316-0c3e-4e7b-8c32-408ad3178865
Bailypottery. (2020). bailypottery.com. Retrieved from bailypottery.com: https://www.baileypottery.com/m-500-001.html

Besserer, A., Torilo, S., Girods, P., Rogaume, Y., & Brosse, N. (2021). Cascading Recycling of Wood Waste: A Review. MDPI - Polymers, 14.
Bin, W., Wei, G., Xuemin, X., Yuqing, D., Pengfei, L., Shouxin, Y., . . . A.M, Abd, E.-A. (2021). Food hydrocolloids. ELSEVIER, 7.

bio-on. (2022, 11 12). bio-on.it. Retrieved from bio-

on.it: http://www.bio-on.it/what.php
Bioplastics Europe. (2022). Bioplastics Europe. Retrieved from Bioplastics Europe: https://bioplasticseurope.eu/about

Bondar, O. (2018, 7 17). oksanabondar. Retrieved from oksanabondar: https://www.oksanabondar.com/wiggy

Britannica. (2022, May 2). T. Editors of Encyclopedia. Retrieved from Encyclopedia Britannica: https://www.britannica.com/science/polymer

Britannica. (2023, 4 3). britannica.com. Retrieved from britannica.com: https://www.britannica.com/technology/sawmill

Cenedella, R. (2023, 4 2). ricardocenedella.com. Retrieved from ricardocenedella.com: https://riccardocenedella.com/ALIMENTA

Chae Hwan Hong, S. H.-Y. (2012). Development of Four Unit Processes for Biobased PLA Manufacturing. Hindawi, https://www.hindawi.com/journals/isrn/2012/938261/.

Charles, G., Alastair, R., Peters, J., & Rogers, B. (2017). Biodegradable materials. Elsevier, 5.

China Brick Machines. (2021). chinabrickmachines.com. Retrieved from chinabrickmachines.com: https://www.chinabrickmachines.com/products.html

Clubzero. (2022). clubzero.co. Retrieved from clubzero.co: https://www.clubzero.co/signup

Clubzero. (2022). clubzero.com. Retrieved from clubzero.com: https://www.clubzero.co/

Cnafield, C. (2008, 4 3). seattletimes.com. Retrieved from seattletimes.com: https://www.seattletimes.com/business/sawdust-once-a-nuisance-now-valuable/#:~:text=In%20the%20cold%20months%2C%20the,burned%20in%20woodstoves%20and%20furnaces.

Dan Howarth, A. H. (2013, 30 10). deezen. Retrieved from deezen: https://www.dezeen.com/2013/10/30/coleoptera-plastic-made-of-beetles-by-aagje-hoekstra/

E. Aytunga Arık Kibar, F. U. (2012). Thermal, mechanical and water adsorption properties of cornstarch–carboxymethylcellulose/methylcellulose biodegradable films. Journal of Food Engineering, 9.

Ecovative. (2022, 8 26). ecovative. Retrieved from ecovative: https://www.ecovative.com/
EDDM. (2020). eddm.es. Retrieved from eddm.es: https://eddm.es/adaptacion-bio-impresora-3d-curso-de-impresion-3d/

Ellen McArthur Foundation. (2014). ellenmcarthurfoundation.org. Retrieved from ellenmcarthurfoundation.org: https://ellenmacarthurfoundation.org/

Elsacker, E. (2018, 12). BiofabForum. Retrieved from BiofabForum: https://biofabforum.org/t/method-of-making-mycelium-leather/218
ENEL, Symbola. (2020). 100 Italian Circular Economy Stories. 220.

European Comission. (2019). pubblications.jrc.ec.europa.eu. Retrieved from pubblications.jrc.ec.europa.eu: https://publications.jrc.ec.europa.eu/repository/bitstream/JRC114889/jrc_wrb_2019_online.pdf

Exportsindia. (2020). exportsindia.com. Retrieved from https://www.exportersindia.com/federique-investment/clay-brick-making-machine-2579955.htm

FabTextiles. (2020, 4). Fab Textiles: Science, craft and entrepreneurship for a global innovation ecosystem in textiles and wearables. Retrieved from FabTextiles website: http://fabtextiles.org/tag/laser-cut-fashion/

fairphone. (2022). fairphone.com. Retrieved from fairphone.com: https://www.fairphone.com/en/
Flux3DP. (2023, 4 1). flux3dp.com. Retrieved from flux3dp.com: https://flux3dp.com/beamo/

Food and Agriculture Organization of the United Nations (FAO). (2020). fao.org. Retrieved from fao.org: https://www.fao.org/faostat/en/#data/FO/visualize

Fullgrown. (2022). fullgrown.co. Retrieved from fullgrown.co: https://fullgrown.co.uk/
Georgiu, M. (2022, 8 26). markosdesigns. Retrieved from markosdesigns: https://markosdesigns.com/Biogun

Georgiu, M. (2022, 8 25). Materiom. Retrieved from Materiom: https://materiom.org/recipe/609

Groover, M. P. (2013). Compression and transfer molding. In M. P. Groover, Fundamentals of modern manufacturing (p. 1124). Wiley.

Habibi, H., & Khosravi-Darani, K. (2017). Effective variables on production and structure of xanthan gum and its food. El Sevier, 11.

Hayakawa, K. (2015). Experimental Creations. Retrieved from Experimental Creations: http://experimental-creations.com/pulp-mold-block/
Hayo Gebauer, L. L. (n.d.). Trig. Trig. Leibal, Berlin.

Henrich Lubke, V. I. (2020). A MULTI-STAGE CASCADE USE OF WOOD COMPOSITE BOARDS. Slovak Republic: Wood Research.

Hubert, B. (2015, 12 5). deezen. Retrieved from deezen: https://www.dezeen.com/2015/12/04/layer-benjamin-hubert-large-hemp-tiles-hexagonal-scale-partition-system-woven-image/

Hurtes, S. (2022, 10 7). nytimes.com. Retrieved from nytimes.com: https://www.nytimes.com/interactive/2022/09/07/world/europe/eu-logging-wood-pellets.html

instructables. (2020). instructables.com. Retrieved from instructables.com: https://www.instructables.com/Wooden-Can-Crusher/

Jerzy Smardzewski, T. K. (2015). Sound absorption of wood-based materials. ResearchGate.
Joon Park, R. L. (2007). Biomaterials: An introduction. In R. L. Joon Park, Biomaterials: An introduction (p. 2). Iowa City: Springer.

Kääriäinen, P., Tervinen, L., Vuorinen, T., & Riutta, N. (2020). The Chemarts Book. In P. Kääriäinen, L. Tervinen, T. Vuorinen, & N. Riutta, The Chemarts Book (p. 194). Espoo, Finland: Aalto University.

Keep Life. (2022, 8 29). keeplife web page. Retrieved from keeplife web page: https://www.keeplife.it/about-kl/mission/

Kofman, P. D. (2007). coford.ie. Retrieved from coford.ie: http://www.coford.ie/media/coford/content/publications/projectreports/coford-connects/ccnpellet_production.pdf

Lasaro Vasquez, E., & Vega, K. (2019). Demo: From Plastic to Biomaterials: Prototyping DIY Electronics with Mycelium. University of California, 4.

Leenderste, J. (2023, 4 2). jeannetleenderste.com. Retrieved from jeannetleenderste.com: https://www.jeannetleendertse.com/

LEGO. (2022, 8 22). lego. Retrieved from lego: https://www.lego.com/it-it/aboutus/discover/stories/plants-from-plants

LEGO. (2023, 4 2). Lego. Retrieved from Lego - Botanical Collection: https://www.lego.com/it-it/themes/adults-welcome/botanical-collection
Libertiny, T. (2020). tomaslibertiny.com. Retrieved from tomaslibertiny.com: http://www.tomaslibertiny.com/eternity

Materiom. (2020). Materiom. Retrieved from Materiom: https://materiom.org/recipe/171

Materiom. (2023, 4 2). materiom.org. Retrieved from materiom.org: https://materiom.org/recipe/203

Mathis, A. (n.d.). Value. Value. Angela Mathis, London.

MOGU. (2022). Mogu. Retrieved from Mogu: https://mogu.bio/

Moore, A. (2022, 3 21). NC State University. Retrieved from NC State University: https://cnr.ncsu.edu/news/2022/03/new-biomaterial-plastic-pollution/

Morelo, M., De los Rios, C., Rowe, Z., & Charnley, F. (2016). A Conceptual Framework for Circular Design. MDPI, 15.

Mylo. (2022, 8 23). Mylo. Retrieved from Mylo: https://www.mylo-unleather.com/stories/

what-is-mycelium/

Notpla. (2022). notpla. Retrieved from notpla: https://www.notpla.com/

ODESD2. (2022). behance.com. Retrieved from behance.com/odesd2: https://www.behance.net/gallery/10536721/Furniture-in-interior

Otero, A. (2022, 9 26). Materiom. Retrieved from Materiom: https://materiom.org/recipe/601

Pacheco, C., & Márquez, V. (2020). lugae. Retrieved from lugae: https://www.lugae.cl/sobre-lugae/

Park, J. B. (1984). Biomaterials Science and Engineering. In J. B. Park, Biomaterials Science and Engineering (p. 1). Iowa City: Plenum Press.

PennState. (2020). Penn State College of Agricultural Sciences. Retrieved from Penn State College of Agricultural Sciences: https://aese.psu.edu/teachag/curriculum/modules/biomaterials/what-is-a-biomaterial

Peráles, S. (2022, 8). mat-wise. Retrieved from mat-wise: https://www.mat-wise.com/egg-shell-capsules

Phys. (2017). Cascading Wood Sustainability. Phys.org.

PostPaperStudio. (2023, 4 2). Instagram. Retrieved from PostPaperStudio: https://www.instagram.com/postpaperstudio/

Precious Plastics. (2020). community.preciousplastics. Retrieved from community.preciousplastics: https://community.preciousplastic.com/academy/research/beyondplastic

Price, J., & Ward, A. (2021). thisnzlife.co.nz. Retrieved from thisnzlife.co.nz: https://thisnzlife.co.nz/make-hay-the-old-fashioned-way-with-this-homemade-hay-baler-built-for-under-150/

Rampino, L. (2018). Evolving Perspectives in Product Design. In L. Rampino, Evolving Perspectives in Product Design - From Mass Production to social awareness (pp. 147-148). Milano: Franco Angeli Design International.

Rofe, B. (n.d.). Weaving Water. Weaving Water. Bela Rofe, Milan.

Rognoli, V., Alessandrini, L., & Pollini, B. (2021). The role of DIY approach in the development of new biofabricated materials. In From human-centered to more than human-design (pp. 118-119). Milano: Franco Angeli - Design International.

Royal College of Art. (2013). rca. Retrieved from rca: https://www.rca.ac.uk/students/jeong-won-ji/

Science Museum. (2020, 4). sciencemuseum.org.uk. Retrieved from sciencemuseum.org.

uk: https://www.sciencemuseum.org.uk/objects-and-stories/everyday-wonders/brief-history-diy#:~:text=DIY%20is%20traditionally%20seen%20to,no%20means%20a%20new%20phenomenon.&text=Detail%20from%20Southern%20Rail%20poster,%2C%20Boy's%20Clubs'%2C%201930s

Scientific American. (2012, 2 16). Scientific American. Retrieved from scientificamerican: https://www.scientificamerican.com/article/bring-science-home-gooey-gels/#:~:text=When%20starch%20is%20heated%20with,process%20is%20known%20as%20gelatinization.

Senge, P. M., & Castedt, G. (2001). Innovating our way to the next industrial revolution. MIT Sloan Management Review, 24.

Shellworks. (2019, 2 22). deezen. Retrieved from deezen: https://www.dezeen.com/2019/02/22/shellworks-bioplastic-lobster-shell-design/

shellworks. (2022, 1 1). shellworks. Retrieved from shellworks: https://www.theshellworks.com/materials

Steinars, V. (2022). valdissteinars. Retrieved from valdissteinars: https://valdissteinars.com/Horsehair-Project

Steinars, V. (2022). valdissteinars. Retrieved from valdissteinars: https://valdissteinars.com/Just-Bones

Steinars, V. (2022, 7). valdisteinars.com. Retrieved from valdisteinars.com: https://valdissteinars.com/Bioplastic-Skin

Talep, M. (2017). margaritatalep. Retrieved from margaritatalep: https://margaritatalep.com/Desintegrame

Technical University of Munich. (2017). Cascading use of wood to ensure sustainability. Retrieved from phys.org: https://phys.org/news/2017-12-cascading-wood-sustainability.html

twi-global. (2002, 10). twi-global.com. Retrieved from twi-global.com: https://www.twi-global.com/technical-knowledge/published-papers/in-the-beginning-the-history-of-laser-cutting-october-2002

University of Guelph. (2022). physics.uoguelph.ca. Retrieved from physics.uoguelph.ca: https://www.physics.uoguelph.ca/torque-and-rotational-motion-tutorial

Valdivieso, C. (2019, 7 23). 3dnatives. Retrieved from 3dnatives: https://www.3dnatives.com/en/pla-filament-230720194/#!

Van-Deursen, L. (2020). lionnevandeursen. Retrieved from lionnevandeursen: https://www.lionnevandeursen.com/kopie-van-biotic
vv

Van-Etten, Q. (2021). The Present is a Gift. Retrieved from isola.design: https://isola.design/

Designer-Projects-The-Present-Is-A-Gift-Rhythms-Of-Nature

Vieira, A., Gurgel, M., & Altenhofe, M. (2010). Natural-based plasticizers and biopolymer films: A review. European Polymer Journal, 10.

Vilnius Academy of Arts. (2022, 06). isola.design. Retrieved from isola.design: https://isola.design/event?eventGK=BXVASMGS&adminGiris=&external=

Wilkes, D. (2018). Chairs that grow on trees! Willows which are transformed into seats over seven years are available to buy for £5,000. The Daily Mail.

Wood and Shop. (2022, 4 2). woodandshop.com. Retrieved from woodandshop.com: https://woodandshop.com/beeswax-wood-finish-for-sale/

World Health Organization. (1994). IARC Monographs on the evaluation of carcinogenic risks - Wood dust and Formaldehyde. WHO, 423.

Y.Zhang, W. G. (2011). Comprehensive Biotechnology (Second Edition). In W. G. Y.Zhang, Comprehensive Biotechnology (Second Edition) (pp. 99-114). Elsevier B.V.

Appendix

APPENDIX A

Recipe 1: Vegetal bio-resin

Ingredients:

- 100 ml distilled water
- 2 g of agar-agar
- 4 g of glycerin

Procedure:

1. Add agar, GLY and water in a cooking pot
2. Mix until agar is completely dissolved
3. Cook at a low fire avoiding the mixture to reach over 80°C
4. Cook for around 15 minutes until it reaches a hard viscous texture
5. Pour the mixture into the desired mold

Recipe 2: Animal bio-resin

Ingredients:

- 120 ml distilled water
- 24 g of gelatin
- 4 g of glycerin

Procedure:

Add gelatin, glycerin, and water in a cooking pot

Cook at low fire for around 15 minutes until the mixture reaches a viscous texture

Avoid the generation of foam in the mixture (so the final piece is free of air bubbles)

If foam appears remove it with a spoon or skimmer

Pour the mixture into the desired mold

Recipe 3: Sugar based bioplastic

Ingredients:

- 200 ml of distilled water
- 4 g glycerin
- 10 g agar-agar
- 8 mg corn starch
- 16 g of powder sugar

Crush the sugar if it is mineralized until it reaches a powder consistency

Mix the agar, corn starch glycerin, water in a pot

Ignite the fire and start mixing until the composite starts solidifying

Add the sugar powder to the mix

Place in a mold and let dry

APPENDIX B

The following recipes were taken from different sources. The tables presented show the original recipe and the further modification done for experimentation purposes. Additionally, each recipe is color coded regarding the type of result obtained (Green for good, red for bad). Additionally, the link for the procedures can be found correctly referenced on the beginning of each recipe.

Recipe 4:

Base: Sodium alginate

Source: Materiom – Coffee composite CoO2 (Materiom, 2020)

Type		*Polymer*	*Filler*	*Plastidizer*	*Solvent*	*Solvent*	
Original	**Ingredients**	Sodium alginate	Coffee	Glycerol	Water	Vinegar	**Total weight**
	Q	4	10	10	200	10	234
	U	g	g	g	g	g	g
	%	2%	4%	4%	85%	4%	100%
Recipe 4.1	**Ingredients**	Sodium alginate	Coffee	Glycerol	Water	Vinegar	**Total weight**
	Q	1	5	10	50	4	**70**
	U	g	g	g	g	g	g
	%	1%	7%	14%	71%	6%	100%
Recipe 4.2	**Ingredients**	Sodium alginate	Coffee	Glycerol	Water	Vinegar	**Total weight**
	Q	1	10	10	50	4	**75**
	U	g	g	g	g	g	g
	%	1%	13%	13%	67%	5%	100%
Recipe 4.3	**Ingredients**	Sodium alginate	Coffee	Glycerol	Water	Vinegar	**Total weight**
	Q	1	15	10	50	4	**80**
	U	g	g	g	g	g	g
	%	1%	19%	13%	63%	5%	100%
Recipe 4.4	**Ingredients**	Sodium alginate	Coffee	Glycerol	Water	Vinegar	**Total weight**
	Q	1	20	10	50	4	**85**
	U	g	g	g	g	g	g
	%	1%	24%	12%	59%	5%	100%
Recipe 4.5	**Ingredients**	Sodium alginate	Sawdust	Glycerol	Water	Vinegar	**Total weight**
	Q	1	10	10	50	4	**75**
	U	g	g	g	g	g	g
	%	1%	13%	13%	67%	5%	100%
Recipe 4.6	**Ingredients**	Sodium alginate	Sawdust	Glycerol	Water	Vinegar	**Total weight**
	Q	4	40	40	200	16	**300**
	U	g	g	g	g	g	g
	%	1%	13%	13%	67%	5%	100%

Recipe 5:

Base: Cornstarch

Source: Walnut shell | Potato starch composite (Materiom, 2020)

Type		Polymer	Filler	Plasticizer	Solvent	Solvent	
Original	Ingredients	otatoe star	Valnut shel	Glycerol	Water	Vinegar	Total weight
	Q	15	250	7.5	60	7.5	340
	U	g	g	g	g	g	g
	%	4%	74%	2%	18%	2%	100%
Recipe 5.1	Ingredients	Corn starch	Sawdust	Glycerol	Water	Vinegar	Total weight
	Q	15	10	7.5	60	7.5	100
	U	g	g	g	g	g	g
	%	15%	10%	8%	60%	8%	
Recipe 5.2	Ingredients	Corn starch	waste (no	Glycerol	Water	Vinegar	Total weight
	Q	15	80	7.5	60	7.5	170
	U	g	g	g	g	g	g
	%	9%	47%	4%	35%	4%	
Recipe 5.3	Ingredients	Corn starch	Sawdust	Glycerol	Water	Vinegar	Total weight
	Q	15	10	7.5	60	7.5	100
	U	g	g	g	g	g	g
	%	9%	6%	4%	35%	4%	
Recipe 5.4	Ingredients	Corn starch	Sawdust	Glycerol	Water	Vinegar	Total weight
	Q	3.0	2.0	1.5	12.0	1.5	20.0
	U	g	g	g	g	g	g
	%	15%	10%	8%	60%	8%	
Recipe 5.5	Ingredients	Corn starch	Sawdust	Glycerol	Water	Vinegar	Total weight
	Q	5.0	3.3	2.5	20.0	2.5	33.3
	U	g	g	g	g	g	g
	%	15%	10%	8%	60%	8%	
Recipe 5.6	Ingredients	Corn starch	Sawdust	Glycerol	Water	Vinegar	Total weight
	Q	35.0	40.0	20.0	100.0	15.0	210.0
	U	g	g	g	g	g	g
	%	17%	19%	10%	48%	7%	

Recipe 7:

Base: Gelatin

Source: Eggshell bio-composite (Materiom, 2020)

Type		Polymer	Filler	Solvent	
Original	Ingredients	Gelatin	Eggshell	Water	Total weight
	Q	5	24	12	41
	U	g	g	g	g
	%	12%	59%	29%	100%
Recipe 7.1	Ingredients	Gelatin	Coffee	Water	Total weight
	Q	7	24	12	43
	U	g	g	g	g
	%	16%	56%	28%	100%

Recipe 6:

Base: Cornstarch + MC

Source: Bioplastic (Materiom, 2020)

Type		Polymer	Polymer	Filler	Plasticizer	Solvent	Solvent	
Original	Ingredients	Potatoe starch	Methylcellulose	N/A	Glycerol	Water	Vinegar	Total weight
	Q	12	15	0	7	300	20	354
	U	g	g	g	g	g	g	g
	%	3%	4%	0%	2%	85%	6%	100%
Recipe 6.1	Ingredients	Corn starch	Methylcellulose	Coffee	Glycerol	Water	Vinegar	Total weight
	Q	12	15	15	7	60	20	129
	U	g	g	g	g	g	g	
	%	9%	12%	12%	5%	47%	16%	100%
Recipe 6.2	Ingredients	Corn starch	Methylcellulose	Coffee	Glycerol	Water	Vinegar	Total weight
	Q	12	15	20	7	60	20	134
	U	g	g	g	g	g	g	
	%	9%	11%	15%	5%	45%	15%	100%
Recipe 6.3	Ingredients	Corn starch	Methylcellulose	Coffee	Glycerol	Water	Vinegar	Total weight
	Q	12	15	25	7	60	20	139
	U	g	g	g	g	g	g	
	%	9%	11%	18%	5%	43%	14%	100%

Recipe 8:

Base: Gelatin + MC

Source: Gelatin-Methylcellulose Bioplastic (Materiom, 2020)

Type		Polymer	Polymer	Filler	Plasticizer	Solvent	
Original	Ingredients	Methylcellulose	Gelatin	N/A	Glycerol	Water	Total weight
	Q	15	12	0	7	300	334
	U	g	g	g	g	g	g
	%	4%	4%	0%	2%	90%	100%
Recipe 8.1	Ingredients	Methylcellulose	Gelatin	Coffee	Glycerol	Water	Total weight
	Q	15	16	15	9	60	115
	U	g	g	g	g	g	g
	%	13%	14%	13%	8%	52%	100%
Recipe 8.2	Ingredients	Methylcellulose	Gelatin	Coffee	Glycerol	Water	Total weight
	Q	15	16	20	9	60	120
	U	g	g	g	g	g	g
	%	13%	13%	17%	8%	50%	100%
Recipe 8.3	Ingredients	Methylcellulose	Gelatin	Sawdust	Glycerol	Water	Total weight
	Q	15	16	20	9	60	120
	U	g	g	g	g	g	g
	%	13%	13%	17%	8%	50%	100%

Recipe 9:

Base: Agar-agar

Source: Turkish coffee waste + Agar-agar (Materiom, 2020)

Type		Polymer	Polymer	Filler	Plasticizer	Solvent	
Original	Ingredients	Agar-agar	N/A	Coffee	Glycerol	Water	Total weight
	Q	1.5	0	7	2.5	40	51
	U	g	g	g	g	g	g
	%	3%	0%	14%	5%	78%	100%
Recipe 9.1	Ingredients	Agar-agar	Methylcellulose	Coffee	Glycerol	Water	Total weight
	Q	12	15	4	5	70	106
	U	g	g	g	g	g	g
	%	11%	14%	4%	5%	66%	100%
Recipe 9.2	Ingredients	Agar-agar	Methylcellulose	Coffee	Glycerol	Water	Total weight
	Q	12	15	10	7	150	194
	U	g	g	g	g	g	g
	%	6%	8%	5%	4%	77%	100%
Recipe 9.3	Ingredients	Agar-agar	Methylcellulose	Coffee	Glycerol	Water	Total weight
	Q	7.5	0	35	12.5	200	255
	U	g	g	g	g	g	g
	%	3%	0%	14%	5%	78%	100%

Recipe 10:

Base: Carboxymethylcellulose (CMC)

Source: The Chem Arts, 17 Wooden Transparency (Kääriäinen, Tervinen, Vuorinen, & Riutta, 2020)

Type		Polymer	Filler	Plasticizer	Solvent	
Original	Ingredients	CMC	N/A	N/A	Water	Total weight
	Q	6	0	0	200	206
	U	g	g	g	g	g
	%	3%	0%	0%	97%	100%
Recipe 10.1	Ingredients	CMC	Sawdust	N/A	Water	Total weight
	Q	1.5	5	0	50	56.5
	U	g	g	g	g	g
	%	3%	9%	0%	88%	100%
Recipe 10.2	Ingredients	CMC	Sawdust	N/A	Water	Total weight
	Q	3	10	0	100	113
	U	g	g	g	g	g
	%	3%	9%	0%	88%	100%

APPENDIX C

See attachments for technical drawings, bill of materials and assembly videos of the products and tools developed.

Thanks

From the bottom of my heart to my mom, my sister, my dad, my family, friends and tutors that supported me, guided me and chirred me through this journey. This would not have been possible without you.

AUTHOR'S INFORMATION

Nicolás Peña Rodríguez

+39 351 9887484
nicolaspenarod@gmail.com
linkedin.com/npena54

Milano, Italy