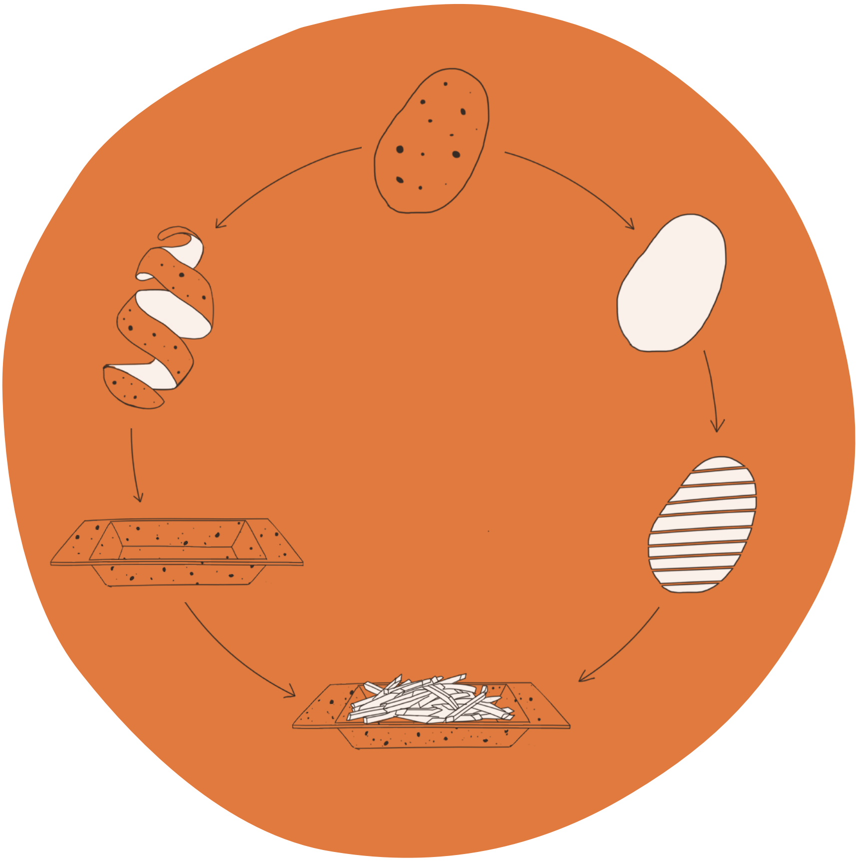

Beyond Plastic

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Master of Arts Thesis 2019 / Aalto University
Collaborative and Industrial Design

Beyond Plastic
An exploration of potato peels as an alternative biomaterial
to single-use conventional plastic.

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Abstract

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More than 60% of plastic produced in recent decades has been discarded into the natural environment or landfills. At the same time, the major segments of overall plastic production are single-use items and packaging, which were designed to be disposed of immediately. Due to their small size and insufficient waste management, these items often leak from the collection systems into nature. As a means of addressing single-use plastic issues, bioplastics were introduced as a replacement for conventional plastics. However, many of these polymers do not biodegrade or require special conditions to fully degrade, which makes the degradation in the natural environment or landfills non-efficient.

This thesis investigates and demonstrates the potential of potato peels as an alternative biomaterial to conventional plastics. As a general approach, this thesis employed a methodology that combined practice-led research and research-led practice within iteration cycles, in order to examine material properties and its processing methods. The primary tangible outcomes of the study were obtained through empirical research and material development; these include numerous material samples that represent different processing techniques, recipe variations, and operation complexity. The resulting application concept is presented as part of the material exploration. All of these research outcomes are further introduced as an open source knowledge.

This study determined that potato peels are a potentially valuable raw resource, due to its low cost, abundance, and interesting material characteristics. Such biodegradable, compostable materials are the most appropriate in certain short-term applications, where biodegradability and compostability are among the core properties.

Keywords: biomaterials, bioplastic, open source, potato peels

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INTRODUCTION

The first chapter provides a brief context overview to familiarise the reader with the thesis topic. Then, it outlines the main objectives and opens up the research questions in order to define the extent of this study. There is also a short notice about Precious Plastic, where the study took place. Finally, the structure of the thesis is included in this chapter.

Context Overview

Since their invention in the last century, plastics have become one of the most extensively exploited materials in almost every area, due to their low cost and versatility. However, only 9% of all plastic ever produced was recycled, while more than 60% was disposed into the natural environment or landfills (Geyer, Jambeck & Law, 2017). Their lack of bio-degradability and insufficient waste management have led to the much-publicized global pollution crisis.

Nowadays, the growing awareness of the importance of waste degradation is pushing social interest towards biodegradable alternatives. Thus far, a number of bio-based and biodegradable polymers has been developed. These kinds of bioplastics are based on renewable sources, such as lignin, sugar, or starch. However, many of these polymers do not biodegrade by their nature, while others, such as polylactic acid (PLA), require special conditions in order to fully degrade, which makes the degradation in landfills non-efficient. Hence, the development of biodegradable alternative materials seems to be one of the long-term solutions, especially in disposable single-use application segments.

There has been a number of projects and research on biodegradable organic sources, e.g., cellulose, food waste, or fungi as composite materials or leather replacement. According to the outcomes of these projects, there are certain material characteristics that can be successfully implemented in targeted single-use applications, such as packaging. Even though the material properties are one of the main criteria, there are other important considerations. In order to push the development of biodegradable polymers and encourage the greater uptake, the initial raw biosource should be inexpensive, accessible on a local level, and easy to work with.

Objectives & Research Questions

This thesis aims to investigate and demonstrate the potential of biomaterials as an alternative to conventional plastics through empirical research and material development. Thus, I started exploring the topic from a quite broad research question and an extensive overview of biomaterials. By means of material research and literature references, I intend to first, narrow down the scope from a wide range of biosources to the target one, and then examine the properties of the chosen biomaterial as well as develop a process of working with it to make it replicable and accessible.

The main research question of this thesis is as follows:

- *What kind of biomaterial would be a reasonable alternative to plastics in single-use applications?*

The supporting questions represent specific parts of the research process:

- *What might be the optimal processing of the chosen biomaterial?*
- *What could be a possible application example for the chosen biomaterial?*

The outcomes of the research are open source and are further introduced to a plastic recycling community, which was the target audience. The emerging insights and results form a visual tool to demonstrate the material value and make the process visible. This includes samples, operation examples, and instructions from simple to more complex, recipe descriptions, and an application concept with a detailed process explanation.

By creating the visibility and open sourcing the resulting knowledge, this thesis contributes to the discussions regarding what bioplastics really are, what properties are crucial for contemporary materials to support a sustainable economy, and what is an optimal product end-of-life management.

Precious Plastic & Online Community

This study took place in Eindhoven, Netherlands, as part of the Precious Plastic project Version 4, alongside other designers, engineers, and helpers, who worked on machine building, recycling, or branding. The team of two, Jannis Kempkens and I, investigated the topic of biomaterials.

The Precious Plastic project[1] was started by Dave Hakkens in 2013 as an initiative to contribute to the plastic pollution problem solving. The general set was the development of several plastic recycling machines and sharing the progress online, providing the instructions, blueprints and any related information on building the machines and producing recycled plastic products. The essential part of this project is the online platform that forms a global community of enthusiastic individuals and enables to collaborate and push forward further development.

Precious Plastic approach for knowledge sharing makes the process look achievable, as it is often illustrated through simple, tangible objects. These examples demonstrate the scale of working with the material, yet the non-professional content serves as a trigger to participate at any skill level. Similarly, the main outcomes of this study were made open source on the community forum[2]. We wrote the section about biomaterials together with Kempkens as our teamwork development and made the topics interlinked as a consistent story with material descriptions, recipes, and simple instructions.

▼ *Precious Plastic by Dave Hakkens. Image 01.*

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[1] Precious Plastic, https://preciousplastic.com/

[2] Community Forum, https://davehakkens.nl/community/forums/

Thesis Structure

This thesis consists of six chapters. The first chapter provides a brief introduction to familiarise the reader with the topic. Then, it outlines the main objectives, research questions, and outcomes to define the extent of this study. The second chapter describes the methodology and introduces a combination of research-led practice and practice-led research as the core approach of this thesis. An overview of the methods, such as empirical research, literature review, documentation, and collaboration, is presented further on.

The following third chapter provides a description of the context and issues in the fields of single-use plastics and bioplastics in order to clarify the primary motivation for addressing this topic. In chapter four, the first research stage and the way of narrowing down the focus is explained. It includes benchmarking of previous projects on various biomaterials and the first empirical experiments on several biosources.

Chapter five focuses on further research of the chosen biomaterial, describing the research flow, recipes, and processes. Numerous documentation photos support the descriptions and illustrate material behavior and properties. The sixth chapter concludes the study, discusses the outcomes and limitations and provides suggestions for further development.

The second chapter describes the methodology employed in this study and introduces a combination of research-led practice and practice-led research as the core approach of this thesis. It is followed by an overview of the utilized methods, including empirical research, literature review, documentation, and collaboration.

METHODOLOGY

2

Core Methodology & Approach

As a general approach, this study undertook a methodology described by Smith and Dean (2009), which introduces a combination of practice-led research and research-led practice. The practice-led approach emphasizes creative practice itself as a form of research which allows the practitioner to "generate detectable research outputs" (Smith & Dean, 2009, p. 5). The creative practice results in the insights which are then followed by their generalization and conceptualization. In this regard, Candy (2006) draws a distinction between practice-led and practice-based research and defines that practice-led approach is "concerned with the nature of practice and leads to new knowledge that has operational significance for that practice" (p. 1), having practice included as part of its methods. This differs from practice-based research, where "a creative artifact is the basis of the contribution to knowledge" (Candy, 2006, p. 1).

Research-led practice, according to Smith and Dean (2009), is complementary to practice-led research. They suggest that "scholarly research can lead to creative work," and define the term as "directed towards the production of practical outcomes," similar to engineering or technology fields (Smith & Dean, 2009, p. 7). In this work, research-led practice is conducted on a relatively small scale of material properties and technologically uncomplicated processes, yet it is an essential part of this study. The primary outcomes of the experimental material research allowed for further exploration of the material properties and a suggestion of an application concept accordingly.

A more tangible representation of this methodology is the iterative cyclic web model (Smith & Dean, 2009). Its basic structure includes a cycle and several sub-cycles within the fields of academic research, practice-led research and research-led practice, all interconnected with a web (Figure 1). This model is based on the concept of iterations, which means that one might follow the circle in any direction, then choose between alternative outcomes focusing only on some of them, and then make another iteration possibly switching the methods.

This thesis employs the illustrated approach as a means to gain knowledge about biomaterials and ways of working with them. It mainly focuses on the right side of the model, proceeding between practice-led research and research-led practice. However, the methodology and data investigation played an essential role in the thesis as part of academic research. Since I do not have a chemistry education, it was crucial to examine papers on material treatment and combine empirical and theoretical research in every iteration phase.

▲ *Figure 1. A model of creative arts and research processes: the iterative cyclic web of practice-led research and research-led practice (Smith & Dean, 2009, p. 20). Image 02.*

The general flow of the study started with researching on a broad topic of biomaterials, benchmarking, and literature reviews, followed by hands-on experiments with several biomaterials. This combination enabled to narrow down the focus and choose one material to work with. The next iteration explored the material properties of potato peels more thoroughly. An overview of the material ability scope was created by reviewing papers on the properties of potato starch and its processing methods to clarify what might be feasible and adapted to the working facilities. The empirical part of this phase included numerous experiments with potato peels based on existing data and some logical assumptions as well as the process implementation in some of the plastic recycling machines. The collected data and experience guided the last iteration — an application concept development. During this phase, the focus was on a mold creation and thorough empirical research, which allowed for the conclusions to be drawn on material behavior and process complexity.

Methods

This thesis operated a combination of methods for data collection and analysis known as multimethod research, as described by Muratovski (2016). As a means to meet the research goals, I addressed both qualitative and applied methods, in particular, the literature review, empirical research, and documentation. This approach enabled to raise theoretical assumptions and validate them simultaneously.

Empirical Research

The hands-on empirical study focused on material properties and resulted in physical samples from basic pressed rectangles to complex objects. To investigate how to treat the chosen biomaterials, I manipulated different variables within several processes. Such variables combined temperature, water amount, time, or pressure, while the processes included extrusion, compression, and pouring. These steps are elaborated in Chapter 4 and 5.
In the phase of designing an application concept, I employed the findings from material experimentation to proceed with ideation, 3D modeling, building a mold, and further experiments on material behavior.

Literature Review

The empirical part of this study required an understanding of the current context around biomaterials, supported by chemistry field research papers, and benchmarking of recent projects and cookbooks about biomaterials. The literature review provided such reference data; however, the scope is limited due to my lack of chemistry education. Nevertheless, this method allowed for a more in-depth understanding of the topic, resulting in insights about different design aspects and processing steps.

Documentation

Empirical data collection for further analysis was essential in every step of this study. The outcomes were gathered with such tools as process diary notes and photo documentation. The notes included small iterations in material experimentation with changing variables. The analysis of this data happened simultaneously in order to correct the recipe and process. Recipe documentation was conducted in two steps: quick notes were written on a piece of paper while cooking, and later were transferred to a document in a more structured way, followed by comments or further ideas.

Writing and sharing posts on the community forum operated as a communication tool. Since the outcomes needed to be reported to a broad audience, all descriptions and instructions were structured and clarified to make the process easily understandable for outside users.

Collaboration

As mentioned earlier, this research was a part of the Precious Plastic Version 4 project, with a team of two developing the topic of biomaterials. I was working in collaboration with another designer, Jannis Kempkens; hence, it is essential to mention the scope of the shared work and individual contribution. Since we had a mutual topic within the project, we aimed to keep the process consistent and correspondent and defined the main objectives and the course of development together as a team. To do so, the preliminary research, benchmarking, and the first material experiments were conducted co-operatively. After the general direction was defined, we focused on two bio sources, potato peels and wheat bran, which were then split between us. Kempkens was developing wheat bran while I was working on potato peels. Further decisions and iterations were shared and discussed continuously between us as well as within the whole Precious Plastic team.

My main contribution at this stage consisted of material research on potato peels, extensive process exploration with samples production, documentation, and application concept development including ideation, 3D modeling, and mold making. The mold making was done in co-operation with Kempkens who designed the heat insulation and helped with the construction, and Friedrich Kegel who executed the CNC of the mold.

The third chapter covers the context and issues in the fields of single-use plastics in order to clarify the primary motivation in addressing this topic. The second part of this chapter describes the key terms and types of bioplastic, illustrates the known biodegradability issues, and leads to the main focus of this study.

CONTEXT

3

The Situation with Plastic Pollution & Single-Use Plastics

In order to highlight the context that served as a starting point of this thesis, the following section provides a brief overview of the current situation regarding global consumption of single-use plastic and provides some numbers to illustrate the scope of the emerging issue.

According to Geyer, Jambeck, and Law (2017), within the period between 1950 and 2015, only 9% of produced plastic was recycled, whereas 12% was incinerated and more than 60% was discarded into the natural environment, landfills, or dumped in uncontrolled open spaces. None of the conventional plastics can sufficiently biodegrade, taking hundreds of years to decompose, and breaking down into microplastics that litter marine ecosystems and contaminate soil and water.

Single-use items and packaging are the major segments of the overall plastic production, with 36% of the total market share (United Nations Environment Programme, 2018). This report stated that among the types of single-use plastics the most frequently found in the environment are beverage bottles, food wrappers, bottle caps, plastic grocery bags, and polystyrene takeaway containers. The estimated annual consumption of some of these items in the EU countries, according to Sherrington et al. (2017), is as follows: 2.5 billion takeaway packaging, 46 billion drinking bottles, and 16 billion coffee cups.

About a half of all plastic packaging applications, or about 30% of the market by weight (Ellen MacArthur Foundation, 2017), was designed to be disposed of immediately, predetermined to end up in landfills or to be incinerated. These applications include small-format packaging (e.g., sachets and tear-offs), multi-material packaging, uncommon plastic packaging materials (e.g., PVC, PS, and EPS, also known as Styrofoam), and nutrient-contaminated packaging, such as fast-food packaging (Ellen MacArthur Foundation, 2017). Due to their small size and insufficient waste management, these items often leak from the collection systems into the natural environment.

As a means of addressing single-use plastic issues and shifting towards the circular economy, some authors (Ren, 2003; Ellen MacArthur Foundation, 2017) suggest replacing conventional plastic with biodegradable and compostable materials and provide related infrastructure for targeted applications, especially nutrient-contaminated disposable packaging.

Ellen MacArthur Foundation and UN Environment (2019):
All plastic packaging is 100% reusable, recyclable, or compostable. This requires a combination of redesign and innovation in business models, materials, packaging design, and reprocessing technologies. (p. 5)

In this regard, this thesis focuses on one of the crucial aspects of the versatile solution — biodegradable materials in single-use applications. While the single-use plastic items hold a significant share of the total plastic production, their biodegradable alternatives are still not used extensively, being, however, an emerging topic worldwide.

Introducing Bioplastic, Its Types & Biodegradability

As illustrated in the previous section, there is increasing attention to biodegradable alternatives to conventional plastics. During the last decade, the rising social and industrial interest in bioplastics has led to their establishment as a rapidly expanding industry with a whole range of developed materials. However, the common perception about these materials by the broad audience differs from their actual features. In this thesis, it is essential to provide a clear definition of what bioplastics are, and what material and biodegradability characteristics they have. This explanation will lead to a gap in the current industry, which is the focus point of the study.

Terms and Difference

According to European Bioplastics (2016), the term "*bioplastic*" defines a plastic material which is either bio-based, biodegradable, or features both properties.

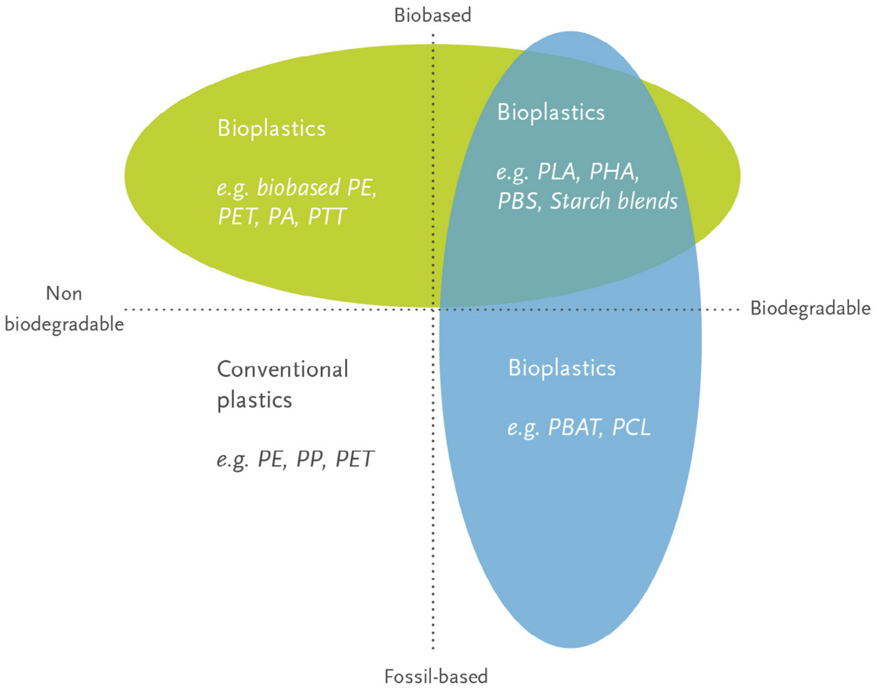
"*Bio-based*" or "*partially bio-based*" plastic is an equivalent to fossil-based polymers, and it holds identical thermosetting and thermoplastic properties. Compared to their conventional petroleum-based counterparts whose carbon molecules originate from fossil resources, such as petroleum or coal, the carbon component of bio-based plastic is derived from a natural renewable resource, e.g., lignin, sugar, cellulose, or starch (Thielen, 2012). This characteristic should be clearly separated from the term *"biodegradable,"* which describes a material property to be broken down and converted into natural substances by micro-organisms, such as bacteria and fungi. There are two types of biodegradation. Aerobic biodegradation occurs with the presence of oxygen, as in the conditions of a compost heap, while anaerobic degradation requires no oxygen and is frequently applied for methane production in biogas plants.

Aerobic biodegradation conditions define the term *"compostability,"* which specifies the material ability to fully biodegrade in a compost heap in a relatively short time. Compost conditions affect this process and differ significantly in *industrial composting* compared to typical *home compost*. In this regard, industrial composting provides optimal conditions for the matter breakdown, with an average temperature of 58–65C°, relative humidity under 98%, and an optimum population of microorganisms (Thielen, 2012).

Types of Bioplastics

In recent years, a number of bio-based materials were launched onto the market. Examples, as shown in Figure 2, are 100% bio-based PET, PP, and PE, as well as blends of bio-based and fossil-based plastic, such as a mixture of PLA and PBAT. The main reason for, and the value in this shift is the development of an alternative to finite crude oil as a source for the aforementioned organic compound. Bio-based polymers are considered a more sustainable and economically stable solution, as their oil content is replaced by potentially renewable bio sources.

However, the production of bio-based compounds involves a significant amount of energy and water; hence, it cannot be considered sustainable. It also evokes debates on ethics, since it employs the land which is typically allocated for human food production. (Tonuk, 2016). Another negative aspect of bio-based plastics is problematic recycling, as well as the potential contamination and incompatibility with other plastics (Alaerts et al., 2018). In addition to this, the non-biodegradability of the majority of bioplastics remains one of the most significant issues that keep this material on a similar level to conventional plastics in terms of environmental and water pollution.



▲ *Figure 2. The three main types within the bioplastics family, classified according to their biodegradability and the resources, from which they are derived (European Bioplastics, 2016). Image 03.*

Consequently, this thesis focuses on bio-based biodegradable types of bioplastic as potentially the most sustainable among these various options. In the current global environmental situation, biodegradability is an essential material property that conforms to the requirements of the circular economy.

Biodegradability of Bioplastics

Along with material characteristics (e.g., chemical structure, or the complexity of the polymer formula), the critical factor that affects biodegradability is the surrounding conditions, where the polymer is disposed of. Conditions, such as the pH, temperature, moisture, and the oxygen content are crucial to consider (Emadian et al., 2017).

In these regards, it is essential to examine if current existing bioplastics are truly able to solve the single-use plastic litter issue and can sufficiently degrade in the natural environment. In their study, Emadian et al. (2017) refer to the extensive research data that has been conducted during the past decade. They analyzed the outcomes of biodegradation tests for bio-based biodegradable plastics (e.g., PLA, PHA, their blends, cellulose blends, and starch blends) under various conditions. The study states that the biodegradation under home composting conditions or in the field soil slows significantly compared to industrial facilities. The reason refers to the lower temperature and non-optimal moisture and pH levels in the natural environment.

Considering the landfill degradation of these kinds of plastics, a study by Kolstad et al. (2012) described two tests on the anaerobic biodegradation of PLA under accelerated landfill conditions. This study concludes that the degradation of PLA in an anaerobic landfill environment will be extremely low and is likely to require a chemical hydrolysis step beforehand.

As described above, current bio-based biodegradable plastics are considered a more sustainable alternative to conventional plastics. However, these materials have an essential gap in their biodegradability in the natural surrounding or within current waste management conditions. Thus, one of the objectives of this thesis is addressing biodegradability and compostability as essential characteristics for disposable single-use products due to their frequent leaks into the natural environment and a high contamination level in food packaging, which means problematic recycling. Compostability, in this regard, might serve as a means of shifting the positioning of these items in the waste management system. Hence, single-use products might be excluded from incineration or landfill streams, being composted with food leftovers instead.

This chapter illustrates the process of narrowing down the research focus from biomaterials in general to potato peels as the main resource for further investigation. The chapter presents the conducted benchmarking of existing projects along with a classification overview of various raw resources and the first empirical experiments on three biomaterials — orange peels, wheat, and potato peels.

Part 1. Overview: **Biomaterials**

Part 2. Empirical Research:
First Experiments

FROM BROAD TO SPECIFIC

4

Part 1. Overview:

Biomaterials

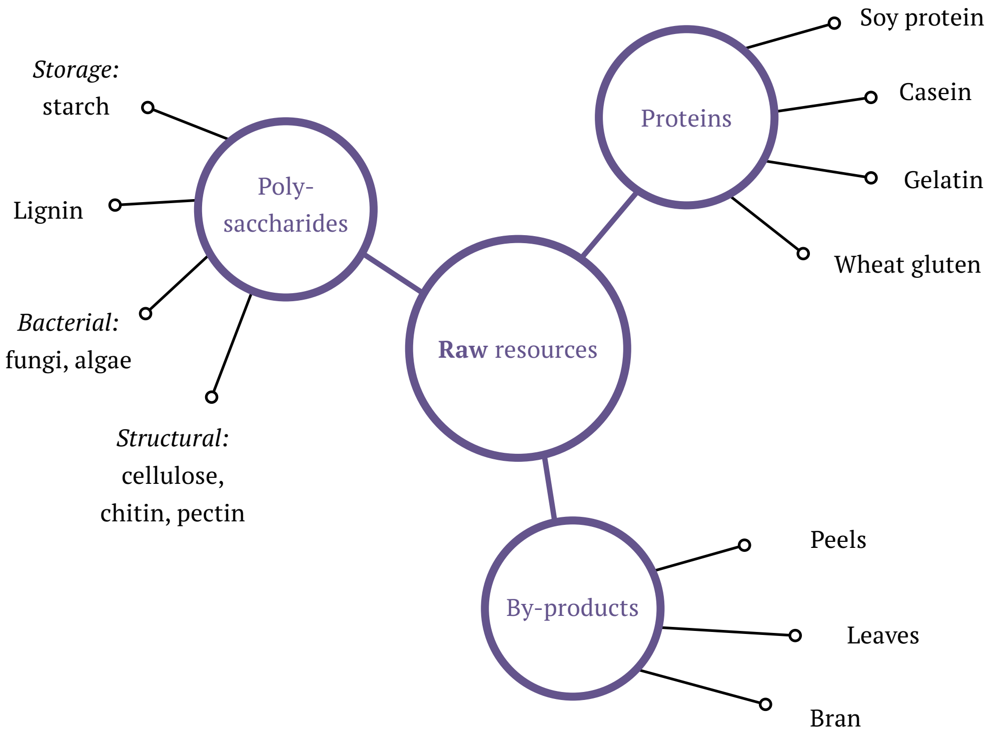
Broader Research

As a starting point of the research, a general overview of existing biomaterials was conducted. The main goal of this stage was to understand the scope of the vast field of bioresources and to structurize them according to their types, in order to outline the major direction of the following study. The main tools employed in this overview were a mind-mapping of the common raw sources for polymers production, as well as a benchmarking of some current applications for various categories outlined in the mind map.

The following classification mind map, illustrated in Figure 3, outlines the most typical resources; however, the whole range of them is more extensive. It should also be noted that the materials from the «by-products» category contain polysaccharides or proteins in their structure, e.g., cellulose, starch, and pectin are parts of peels or leaves. Nevertheless, they represent a separate category, and the logic behind this kind of classification is that all the listed biosources are considered as a possible starting point, utilizing the materials as they are. This means that, e.g., peels should be used as a biomaterial, not as just a source for starch or pectin.

This section will briefly explain the core characteristics of each category. Polysaccharides are the most abundant natural polymers produced by plants (Jeevahan et al., 2017). They are also a compound of bacterial and fungal cell walls. Polysaccharides, e.g., cellulose participate in forming the rigidity of plant structures like stems and grass blades. Chitin is a robust structural polysaccharide that comprises the shells of several crustaceans, including lobsters, crabs, and shrimp (Brigham, 2018). Polysaccharides are frequently utilized for edible films production and as thickeners due to their viscosity.

Proteins are ubiquitous biomaterials with two main types — enzymes and structural proteins. Structural proteins like collagen or gelatin obtain mechanical properties that make them useful in a variety of applications, such as medical, due to their biodegradability and biocompatibility (Brigham, 2018). Proteins are often used for films production, and the mechanical properties of protein films are considered better than that of polysaccharides (Jeevahan et al., 2017).



▲ *Figure 3. Classification mind map of some common raw resources.*

As mentioned earlier, the by-product category biomaterials contain proteins and polysaccharides in them. This category represents possible directions for utilizing the listed sources by transforming them into valuable products. Two application examples are provided in the next section Benchmarking review.

Benchmarking Review

This section provides examples of existing projects and applications. These are only some illustrations of the abovementioned biosource categories from all benchmarking outcomes found on this step.

Evoware

An Indonesian company Evoware[1] has introduced an alternative to small single-use plastic packaging. The company's product range includes coffee and dry seasoning sachets, soap packaging, and edible food wraps for burgers, bread or sandwiches.

Their products are made out of unaltered seaweed, which can be safely eaten or discarded for biodegradation. An interesting property of this material is its ability to dissolve in hot water, which means that their sachets are consumed immediately with food, leaving zero waste behind. Evoware's approach is an insightful example of employing specific material properties for a particular application.

◀ Seaweed products from Evoware. Image 04.
▶ Wheat bran edible cutlery from Biotrem. Image 05.

Biotrem

Biotrem[2] is a producer of edible wheat bran tableware, including plates, bowls, and cutlery. All these products are made with only two ingredients, wheat bran and water, which are pressed with heat in a mold. Biotrem's tableware is fully biodegradable in a month and also edible, whereas the processing technology is relatively simple.

These products are a promising solution for, e.g., festivals where a significant amount of disposable plastic is normally consumed. Such application of this material's short life span and its approachable technological process have inspired one of the two development directions for our team, and wheat bran has become a target biosource for further research.

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[1] Evoware, http://www.evoware.id/

[2] Biotrem, https://biotrem.pl/en/

Ecovative Design

Ecovative[3] is a biotech company that develops materials from mycelium. Mycelium is a "root-like" network structure of a fungus that can grow into any shape. The company develops biodegradable packaging materials, animal-free leather replacement, and meat alternatives.

For instance, MycoComposite™ is a composite biomaterial based on agricultural hemp waste with mycelium utilized as a binder. Ecovative's MycoFlex™ represents strong "leather-looking" pure mycelium foam that can be applied to textiles, footwear, or technical wear. This approach allows for the reduction of greenhouse gases and the cattle-rearing land use, also providing a more sustainable option than synthetic leather.

▶ Mycelium "leather" developed by Ecovative Design. Image 06.

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[3] Ecovative Design, https://ecovativedesign.com/

Chipsboard

A British startup Chip[s] Board[4] employs potato waste to create rigid boards for interior applications, as well as fashion accessories. The company implements circular economy principles in the production, products' end-of-life management, and collection strategies.

This is also an example of turning a local waste stream into products within a collaboration with a potato producer, achieving zero production waste.

Recipe Cookbook: Materiom[5]

This source is helpful in search of recipes for various biomaterials. The data is open source, and covers locally abundant biomass, applying green chemistry methods in the recipes. The library is categorized according to the ingredients (proteins, composites, sugars), processes (3d printing, mixing, baking, casting), tools, and difficulty levels.

▲ Potato peels boards produced by Chip[s]Board. Image 07. ▶ Biomaterials by Materiom. Image 08.

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[4] Chip[s]board, https://www.chipsboard.com/

[5] Materiom, https://materiom.org/

Food Waste & By-Products

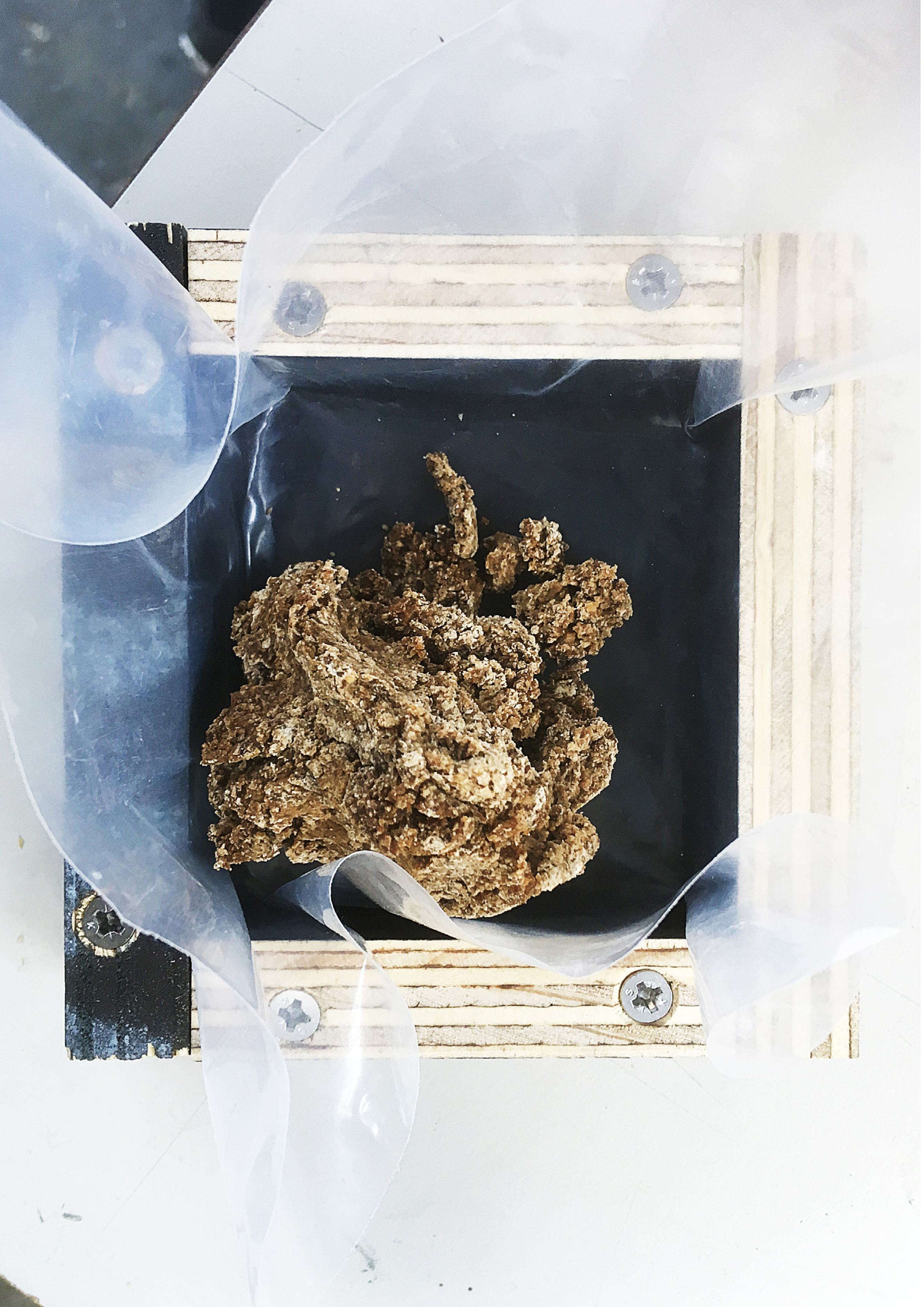
Having in mind the outcomes from the general overview of biomaterials and benchmarking of existing projects, we as a team went through a series of discussions in order to define the next steps. At this moment, we decided to exclude from future research the most time-consuming biosources, such as growing microorganisms, and the less accessible sources which are harder to receive as raw material, such as chitin. Consequently, the main criteria for further focusing was the accessibility and price, as well as the current data about biosources which are frequently used as a base for bioplastics, e.g., starch. Thus, the drawn conclusion indicated that the optimal combination of these would be a food waste and by-product stream. The following data illustrate the current global waste stream scopes and applications.

In food production, a significant part of by-products and waste including peels, skins, and oils is considered unavoidable (World Biogas Association, 2018). Currently, this kind of waste is treated as a non-valued material, and the most common streams for it are animal feed, recycling for soil fertilizer production, incineration, or disposal to landfill or sewer.

However, the direction of turning waste into valuable material is already emerging, as some industries consider it as a cheap raw resource for further production. For instance, the report by World Biogas Association (2018) encourages the cities to turn their waste into biogas, compost, or power. At the same time, these by-products potentially are a beneficial resource for biomaterials and bioplastics development.

Another aspect taken into account represents the issues in bioplastics industry mentioned in the previous chapter, such as the use of lands exclusively for bioplastic sources, water and energy utilized for their production, as well as the manufacture costs. Hence, in order to minimize the negative impact of these prospects the source for further material research is chosen to be a waste stream. At the same time, the assumption is to employ the generally low cost of renewable resources and to create valuable material from almost any biowaste. Examples of such approach are aforementioned companies Chipsboard and Biotrem who make their product from by-product wheat bran and potato peels.

At this stage, from a wide variety of sources within the undervalued waste stream category, we narrowed down the scope to three — two starch-based biosources, potato peels and wheat by-products, as well as orange peels. These were among the most accessible sources on our local level since they were available from our community kitchen. In fact, the kitchen almost entirely supplied my further research with the raw potato peels in all experiment stages. In this regard, this study started employing zero waste production principles on a small scale from the beginning.



Part 2. Empirical Research:

First Experiments

Mini-Lab

First, I will briefly mention the working environment. Being part of the Precious Plastic project, we worked altogether with other members in the workspace with unlimited access to all Precious Plastic machines as well as metal and wood processing facilities.
Before our team started working on biomaterials, we built and set up the ‘mini-lab’ - a small zone, partially separated from the rest of the workspace.

◀ Potato peels mass before compression into a wooden mold. ▶ Mini-lab.

Orange, Wheat, & Potato

While working on the general overview of biosources and benchmarking, as a team we made several experiments with three chosen materials. This step was meant to be short, aiming to receive the first impression of the behavior of these biomaterials and to set up the process. The first experiments were not properly structured, but the workflow improved with the gained experience. Since the time frame was limited, it was not possible to continue working on multiple biosources. Further research on these would be beneficial.

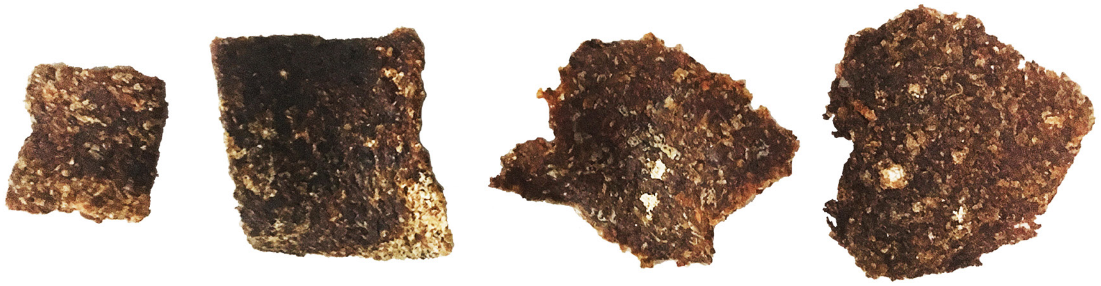
In order to proceed with the recipe variations, the primary compounds used in bioplastic production should be taken into account. In general, the main components are 1) *Filler* — it increases the strength, 2) *Binder* — it binds the filler fibers together, and 3) *Plasticizer* — it adds flexibility to the material. In this study, orange and potato peels were used as a filler, different kinds of starch served as a binder, and glycerol was added as a plasticizer in several recipes.

▼ *Wheat gluten sample.*

Wheat

I participated in the experiments with wheat only to a short extent in the very beginning, before Kempkens took this biosource, wheat bran in particular, as his main focus.

We started with washing wheat flour to separate gluten from starch. The starch was left for drying for further use.
The main observations for wheat gluten:
The material is very stretchy and "leather-like" when still wet, but gets hard and brittle after drying. All samples started rotten; hence, the addition of a preservative is needed. Further research on maintaining the flexibility properties might be a direction for leather replacements.



▲ *Orange peels samples, processed in the compression oven*

The recipes and processes, extracted from my notes, are presented in Figure 4. This data, along with the photo documentation on p. 45 serves as a reference to the following description.

Orange Peels

We started exploring this biosource because according to our benchmarking research, the outcome material is relatively strong. In the cooking process, a binder needs to be added, as the biomaterial itself does not contain it. In this regard, some recipes were found online and tested.

Main ingredients: Orange peels, starch, water, and glycerol.
Wooden mold: Experiments started with pressing the mass in a simple rectangular wooden mold under the manual hydraulic press and leaving to it dry — this resulted in a weak sticky material with multiple cracks.
Starch types: Brief research was conducted on different kinds of starches and their characteristic difference. For instance, tuber starches are considered to be stronger (Soomaree, 2016) and require a lower cooking temperature than corn starch. Hence, in further experiments, the focus was mostly on tuber starches, such as tapioca or potato starch.
Heat press: The next step explored the compression oven. A more detailed description of the oven is provided in the next chapter under the section "Process: Compression." The observed samples were still moist and flexible, as the water did not evaporate.
Metal mold: In order to press a sample in the oven, a square steel mold was built. The size was smaller than the wooden mold. This material is more heat resistant, and due to its strength, it allows for applying higher pressure.

Potato Peels

Potato peels were another promising biomaterial as resulted from the preliminary research. The most interesting characteristic of this biosource is the presence of starch; hence, it requires little or no additional binder.

Cooking in a pot: The mass was cooked in a pot before further processing to activate the gelatinization. Chapter 5 provides details on the gelatinization process in the section "Peels and Starch."

Additional starch: In the first experiments, all samples were cooked with additional starches, such as wheat, tapioca, and corn.

Acetic acid: Several samples were prepared using acetic acid. According to the research data, it makes the starch more homogeneous by breaking its amylopectin chains. The starch structure is described in Chapter 5.

Pouring: Some samples were made without applying pressure. Pouring resulted in a loose and uneven surface.

Hydraulic press: Pre-cooked mass was pressed under the manual hydraulic press. The outcome samples were very moist and deformed with time after drying.

Heat press: For some samples, the pre-gelatinized mass was pressed in the compression oven. According to different water ratio and cooking temperature, some of them appeared wet and deformed with time. All samples produced with both heat and hydraulic press were processed using the same wooden and steel molds mentioned in the Orange Peels section.

Conclusion

As can be seen from the sections above, we tested several aspects of biosources processing within a short period. These included various additives, such as glycerol or starch, two different materials for the mold, and several processes, such as pouring, pressing pre-cooked mass under the hydraulic press, and applying heat pressure in the oven.

Such variables, as water ratio, time, temperature, and pressing method affect the surface appearance and overall material strength significantly and are the subject for further examination.

From this moment on, I undertook potato peels as my focus biomaterial. As a raw source, potato peels are widely spread, renewable, and inexpensive. Even though orange peels are similar in these aspects, I concentrated on potato peels due to their starch component. In this regard, two core compounds — a filler and a binder are present in the material by default.

Since the obtained potato peels samples became generally hard and sturdy after drying, this material property defined the main direction for the material development. At the same time, one sample appeared to be "leather-looking" in its wet condition. This inspired for further exploration of flexibility properties as a side experiment.

Acetic acid was not employed in further research since this study focused on physical treatment only.

▼ *Potato peels samples, processed in the compression oven*

Wheat

Gluten

11.10.18 Separated from flour and left to dry: one part as is, second one mixed with glycerol, third wrapped over a glass. All three hardened to a different extent and started rotting. The thin layer is leather-like and very stretchy when wet, and hard and brittle when dry.

Starch

11.10.18 Separated from flour (white and whole grain) and left to dry. One part mixed with some glycerol. All ground to powder.

Bran

Yannis is doing this part now

Orange Peels

Ground pieces

16.10.18 Mixed 60g with corn starch 100g / water / glycerol 48ml. Pressed mass is very sticky and soft. Left to dry in the air: the thin one has got cracks all over, the thick one is pretty soft

Goals: Try different starch, heat press

18.10.18 Mixed 50g with tapioca starch 15g & water, cooked; heat press oven 200C 10min (+heating up) - failure! 100C 17min - moisture stays inside.

Goals: A different mold, plaster?

Mixed 50g with tapioca 13g + acetic acid 20ml, cooked; one part pressed, other part mixed with glycerol and pressed.

Potato Peels

Ground pieces

16.10.18 Cooked with wheat starch / acetic acid. One part was pressed without mold - didn't work. The second part was mixed with starch (poorly dissolved) and pressed - wet material is leather-looking and flexible; hard when dry.

Goals: More leather-looking material, try pouring and pressing; sheets

17.10.18 Blended fresh peels in a mass. One part left as is, second part mixed with acetic acid and left to dry as a thinner layer.

18.10.18 The mass with acid got drier; put in the heat press-?

19.10.18 Two possible ways: hard material and leather-like. For the hard one - dissolve tapioca in acid, cook with the peels, press.

Dry powder

17.10.18 Mixed with pre-cooked corn starch (acid-free); pressed; dried in the oven. The dry sample is hard, brittle, has cracks.

Goals: Sheets, bricks

▲ *Figure 4. Extract from my notebook with recipes & processes. Some notes might be incomplete.*

Chapter five focuses on further research on potato peels and exploration of their material properties. It describes the research flow, recipes, and processes, such as compression, extrusion, and compression in a heatable mold. Numerous documentation photos support the descriptions and illustrate material behavior and properties. Finally, the chapter provides an overview of material characteristics, based on the observations throughout empirical experiments.

POTATO PEELS EXPERIMENTS

5

Part 1. Overview: **Peels & Starch**

Part 2. Process: **Compression**

Part 3. Process: **Extrusion**

Part 4. Concept: **Take-away Container**

Part 1. Overview:

Peels & Starch

As previously mentioned, this thesis focuses on one type of biowaste — potato peels. This section elaborates on potato peels as a by-product stream, providing some numbers about the production and waste. In general, peels appear interesting for further research as they showcase great potential as an inexpensive, abundant biosource. Moreover, the main ingredient of peels is starch, which has optimal properties for bioplastic and is already extensively employed for film production. Consequently, in my research, I examined the structure of starch to understand better its characteristics and what to expect from it.

Adding Value to the Potato Waste Stream

The potato is one of the most common food crops worldwide after rice, wheat, and corn (Gebrechristos & Chen, 2018), with industrially generated peel waste in the range of 70 and 140 thousand tons annually (Wu, 2016). Potato peels range from 15 to 40% of initial potato mass in the industrial production, depending on the peeling method (Sepelev & Galoburda, 2015), such as steam, abrasion, or lye peeling.

This by-product is still considered zero-value and is utilized for, e.g., animal feed. However, recent studies have been raising awareness of its potential to be applied in various sectors, due to its numerous valuable compounds including starch, lignin, and non-starch polysaccharides (Priedniece et al., 2017; Sepelev & Galoburda, 2015; Wu, 2016)

There is a number of studies that focus on potato starch properties and the possibilities to process it into plastics. At the same time, some other studies suggest ways to apply potato by-products, aiming to minimize the amount of industrial waste. According to them, potato peels might serve as a basis for phenol extraction, edible film production, ethanol, lactic acid, and enzyme production through fermentation. (Sepelev & Galoburda, 2015). However, many of these processes only extract the necessary ingredients from peels, without employing the rest of the material. Thus, this study assumes a proposition to use whole potato peels, which have fibers and enough starch in them, as a biomaterial.

> *"To solve the future and current problems of the global environment issue, conversion of food waste into environmentally friendly product through conversion to value-added products is mandatory."*
>
> [Gebrechristos & Chen, 2018]

What is Starch?

The main components of potato peels are starch, cellulose, hemicellulose, and fermentable sugars, from which the starch amount is approximately 50% of the dry weight (Arapoglou et al., 2010). Thus, since it is the major ingredient, a number of papers about the structure of starch and some of the known treatment processes were examined to gain a better understanding of potato peels as a biosource and to identify a starting reference for further experimentation.

Starch functionality is mainly defined by its components and their ratio. It is composed of amylose and amylopectin macromolecules (Xie, Halley & Avérous, 2012), which create semicrystalline granules. Amylopectin forms crystalline regions that maintain the structure of the granule and amylose forms amorphous regions, which are less dense, absorb more water and are able to form a paste (Zavareze & Dias, 2011).

In general, starch treatment starts with the disruption of the semicrystalline structure by heating it in the presence of water. This leads to the formation of "paste" or "gel," which is called *gelatinization* (Shrestha & Halley, 2014). The process is irreversible and starts at around 60°C. Further cooling is known as *retrogradation* and represents a formation of a tightly packed structure with increased firmness or rigidity of the starch (Shrestha & Halley, 2014). In this regard, due to both the gelatinization properties and strong intermolecular bonds, starch is considered a valuable source of biopolymers and can be utilized in various industrial processes, such as injection molding, extrusion, compression molding, and film casting (Xie, Halley & Avérous, 2012).

There are two common ways of starch modification — 1) *physical*, including heat-moisture treatment, pre-gelatinization, and milling, and 2) *chemical*, such as acid hydrolysis, cross-linking, or oxidization. After examining studies by Shrestha & Halley (2014), Zavareze & Dias (2011), Hoove & Vasanthan (1993) on starch modifications, I considered the principles of heat-moisture treatment (HMT) to be easily replicable and interesting for implementation in this thesis. It is conducted under restricted moisture content (10 – 30%) and higher temperatures (90 – 120°C). The main benefits of this treatment are increased heat and shear stability and decreased granular swelling during gelatinization (Zavareze & Dias, 2011), which means that the granules absorb less water and, hence, shrink less during retrogradation. Other treatment types were beyond the scope and time frame of this study to thoroughly examine.

In the following research, this study aimed to further investigate the potential of potato peels within uncomplicated "low-tech" process, keeping in mind both theoretical and empirical research outcomes stated above. As a side note, I should mention the fact that being stated as "low-tech," the following techniques still require equipment for processing the material.

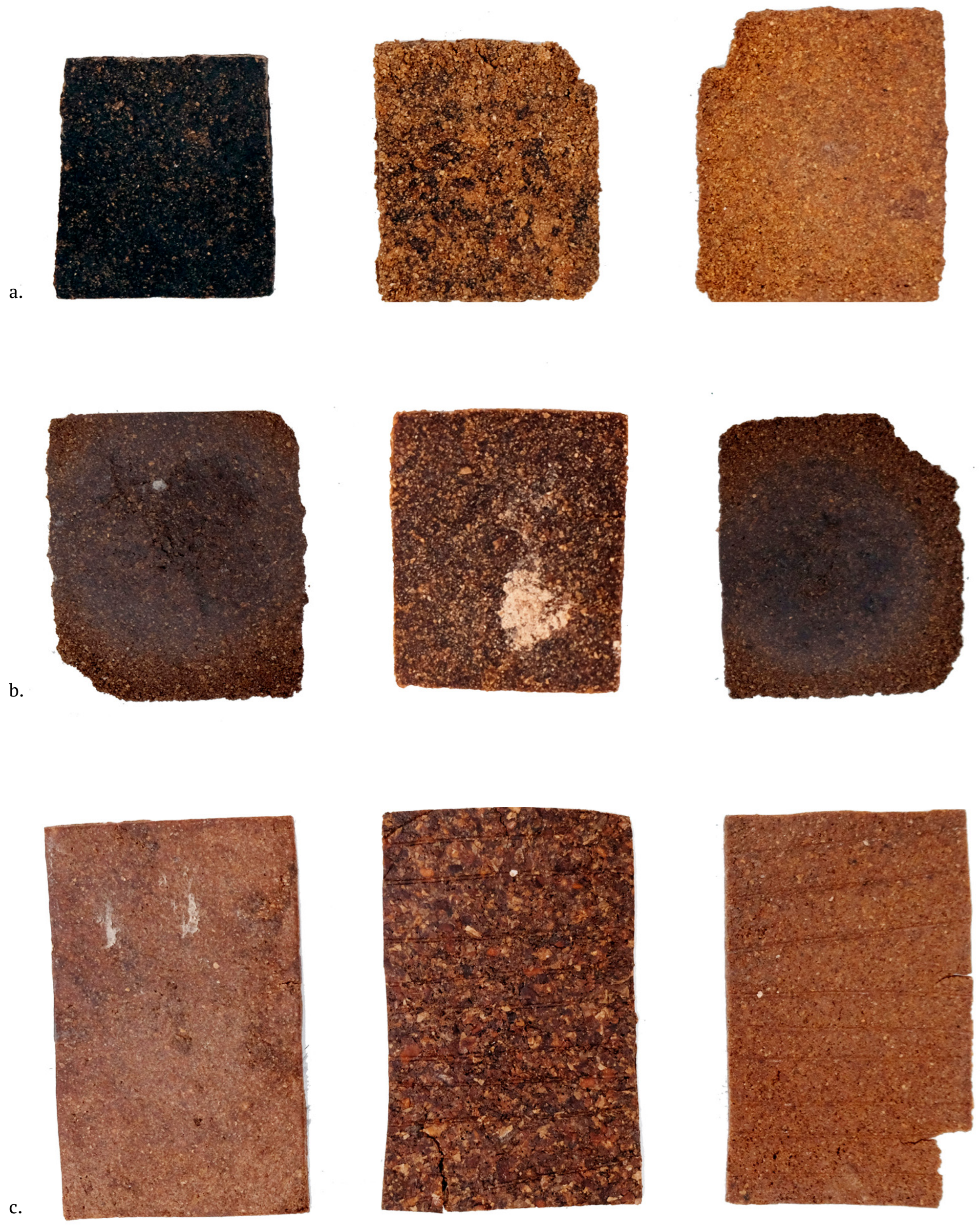
Starter Material: Preparation

Before going further into the process, I will briefly describe the starter material and the preparation of it. In the experiments, I mostly used dry ground peels. The dry starter allowed for preventing fungus growth and achieving a more precise water ratio calculation in the recipes. Other ways of processing were also tried, e.g., grinding fresh peels in a blender first and then drying. However, the described way appeared to be more approachable. The preparation process is as follows:

1. Fresh peels are dried in an oven. Although there might be more energy efficient ways to dry them, this was the available option at that moment.

2. Dry peels are ground in a blender or a coffee grinder. The size varies from a fine powder to bigger flakes according to the time and speed of grinding.

3. The ground dry matter is stored in containers.



▲ *Samples of pressed potato peels.*
Rows a. & b. — Hard material. Row c. — Flexible, 'leather-like' material with additional glycerol.

Part 2. Process:

Compression

As can be seen from the papers above, the basic requirement for starch and, hence, potato peels processing is the application of heat in the presence of water. This activates the starch gelatinization and makes the mass manageable and flexible. Then, in order to shape the mass, it should be compressed in a mold. The following section provides the descriptions of the techniques and machines utilized in this study.

Used equipment:	**Used materials:**
Compression oven	Potato peel powder
Manual hydraulic press	Potato peel flakes
Square steel mold	Water
Heatable mold (bowl)	Starch
Cooking pot	Glycerol
Scales	
Iron	
Baking paper	

General Technique

In the compression process, I was using two main set-ups — heat pressing in the compression oven and cold pressing of the pre-gelatinized mass under the manual hydraulic press. The goal of this step was to continue material exploration which had been started during the first experimentation. In order to understand the compression process and potato peels behavior, several aspects were taken into account: ingredient ratio, time, temperature range, as well as pre-gelatinization, pressing, and drying.

In general, the cold compression was done as follows:
1. The mixture is pre-gelatinized in a pot at 60 - 80°C.
2. Viscous mass is loaded into a mold and pressed in the hydraulic press.
3. The sample is removed from the mold and left for drying for 3-5 days.

The general heat compression process:
1. The mixture is loaded in a mold without pre-gelatinization, in between baking paper layers. In the first experiments, the mass was pre-cooked, but later this step was excluded.
2. The mold is pressed in the compression oven at 100 - 180°C for 10-15 min.
3. The sample is removed and left for drying if needed.

◀ *Compression oven by Dave Hakkens. Image 09.*

Compression oven
The machine consists of an electric kitchen oven that heats the material, and a hydraulic jack that presses it into a mold. The electronic controllers for the oven set the temperature. After the mold was placed in the preheated oven, the turning of the hydraulic jack pushes the tray against the ceiling. This creates pressure, and the material starts spreading inside the mold. After the desired time, the hydraulic jack is released, and the mold can be taken out and opened.

Directions

I investigated three paths within the compression process. Some of the process notes are presented in Figure 5 on p. 60 — 61, along with photo documentation on p. 62 — 63.

Hard Boards — the core direction for the compression. Potato peels obtain the characteristics that enable to naturally create a sturdy hard material, due to the presence of starch that binds the fibers together. When the moisture, which serves as a plasticizer in the mass, evaporates, the outcome material becomes hard.

Main observations
- In the heat compression, the pre-gelatinization step can be excluded, since it can happen directly in the oven.
- Cold pressed samples deform stronger than heat pressed due to the higher moisture content which did not evaporate.
- An attempt to exclude additional starch is successful. Hence, the actual starch amount in peels is sufficient for binding fibers together.
- Some moisture still stays inside the mold. Assumed reasons are 1) baking paper prevents evaporation 2) the mold should be designed with air channels 3) the water ratio and temperature are not optimal.

▶ *Compressed potato peels. Flakes and fine powder.*

▶ Compressed "potato leather."

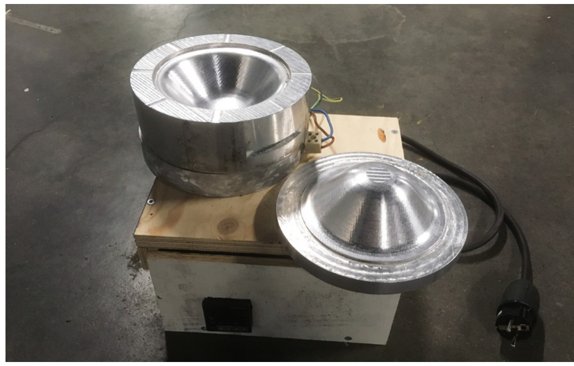
"Potato Leather" — a side experiment on exploring possibilities to make the material flexible. Potato peels were mixed with glycerol and additional starch, pre-cooked, pressed in the compression oven in a thin steel mold. Resulted material was very flexible and "leather-looking." However, the obtained samples are not strong enough and can be torn apart. The time frame of this study did not allow to continue the exploration of these properties, and further research is required.

Main observations

- Cold pressed samples were weaker and wetter than heat pressed ones.
- The baking paper was removed. Due to glycerol, the «leather» mixture sticks to metal stronger than the regular mixture without it.
- The flexibility has decreased in the long term after several months.
- The iron press was tried in order to provide better air circulation, and hence, an assumed improved moisture evaporation. However, the evaporation did not increase, and the compressure from hand ironing was not sufficient

Heatable Mold — the first attempts of compression in a heatable aluminum mold. As assumed, a self-heated mold should provide a more efficient and fast material cooking along with the pressure obtained from the manual hydraulic press. The heating elements are made from kitchen hot plates and wired to a PID controller. The described mold was built by Jannis Kempkens.

The process is as follows:
1. The temperature is set on the PID controller, and the mold heats up.
2. The mixture is loaded into the mold and closed.
3. The mold is placed in the manual hydraulic press and pressed under five metric tons for the required time.
4. The mold is opened, and the sample is removed.



▶ Opened heatable mold and the PID controller box.

Main observations

- Since the water evaporation was still under investigation, the first assumption was to increase the temperature while decreasing the time. Several unsuccessful samples were pressed at the range between 95 — 120°C. At 120°C, the surface of the material was stuck to the mold, while the inner layer was excessively wet. When the mold was opened, the sample was torn between its parts due to the stickiness.
- The most even and firm sample was cooked at 80°C for 15 min. However, it was still moist and shrank after three days while drying.
- Some sunflower oil was added on the mold as a mold release in order to open it more easily. As an additional benefit, it gave a pleasant smell of fried potatoes.

▼ Bowls from potato peels pressed in the heatable mold.

Dry powder

31.10.18 Tried to skip one cooking step in the process using the same recipe with additional tapioca starch.
1. Too little time pre-cooking (cold press) results in very uneven crumbling surface texture. 2. Pre-cooked sample + cold press gives an even but not smooth surface, is flexible and deforms later due to the extra moisture. 3. No pre-cooking + heat press gives a more smooth surface and strong edges, but uneven in the center. 3. Messed up a sample with less peel powder; pre-cooked + heat press; looks similar to the previous one but lighter color, also strong edges, fewer cracks in the middle. 4. Second try-out of peel powder + water without additional starch - interesting one - is strong so looks like peels have enough starch themselves. Pre-cooked + heat press. Weak crumbling edges, uneven center, but parts of it are strong and smooth. 5. “Leather” - same recipe + glycerol. Pre-cooked + cold press, very flexible and even, still has much moisture.
Goals: Try a no-starch recipe with +/- water amount. Wait for the leather to dry, try to heat press it.

01.11.18 Made a thinner mold, tried a different amount of water (no starch) to check how it would affect the material texture — fewer water results in a more even middle part but dry crumbling edges. More water gives stronger edges, but a weaker moist middle part with cracks and the whole sample starts deforming when drying.
Goals: Find a solution for the mold. Current mold doesn’t let the moisture go out (baking paper might also be a reason). Try wood; take the upper layer of baking paper out.

02.11.18 No upper layer of baking paper-? Tried heat press leather sample; nice texture, drier than the cold-pressed one, still pretty weak and can be torn apart easily; gets even weaker with time.
Goals: Experiment more on the leather - try to put more binder to make it stronger

05.11.18 The first leather piece got super weak and got demolished. Building another mold, made a thinner layer + stripes on the upper lid, polished it.

07.11.18 Made a nice leather sample (pre-cooked + heat press), the texture resembles real leather a lot. It is done in the new mold without a second baking paper layer. Material with glycerol in it sticks to metal stronger than no-glycerol. UPD: Not strong enough, doesn’t resist tearing.
Goals: Try bigger ground pieces for both leather and hard material. Try iron press to check if letting the moisture out affects the surface.

09.11.18 Iron pressed both leather and hard material. Not enough pressure in general. Leather: the upper surface is baked while the bottom stays wet. Also the mold is cold so doesn’t help evaporation; when pressing between 2 baking paper layers only a lot of water condensate in between (so probably the thing is not only the air circulation but also the material of the mold which should not stick to the mass and allow to get rid of paper layer). Hard board: moisture evaporation gives a more even surface without the wet center.
Goals: Try extrusion machine.

12.11.18 Extrusion machine try-outs. Appx. 250 C. Too much heat cooks the material and makes it stuck inside the tube. Pieces were dry with the glossy surface because of the polished metal part. The second try was too weak with too low temp, around 50 C. The third try went better with around 100 C. If extruding in layers, they can stick to each other when still hot - 3d printing direction, but maybe only small objects otherwise layers cool down.
Goals: Try extrusion in a mold.

14.11.18 Mold extrusion. 1. Cold mold, 100C in the tube, heated up later. It gives an even but a bit rough surface, wet and flexible in general. 2. Pre-heated mold 250C, 100C in the tube. Gives a smooth glossy surface, small details and text are sharper, also wet. Both hardened within several days, strong when dry.
Goals: Get rid of the moisture. Try higher temp; less water; different mold pre-heating temp; air-? Also, find ways to achieve different hardness levels.

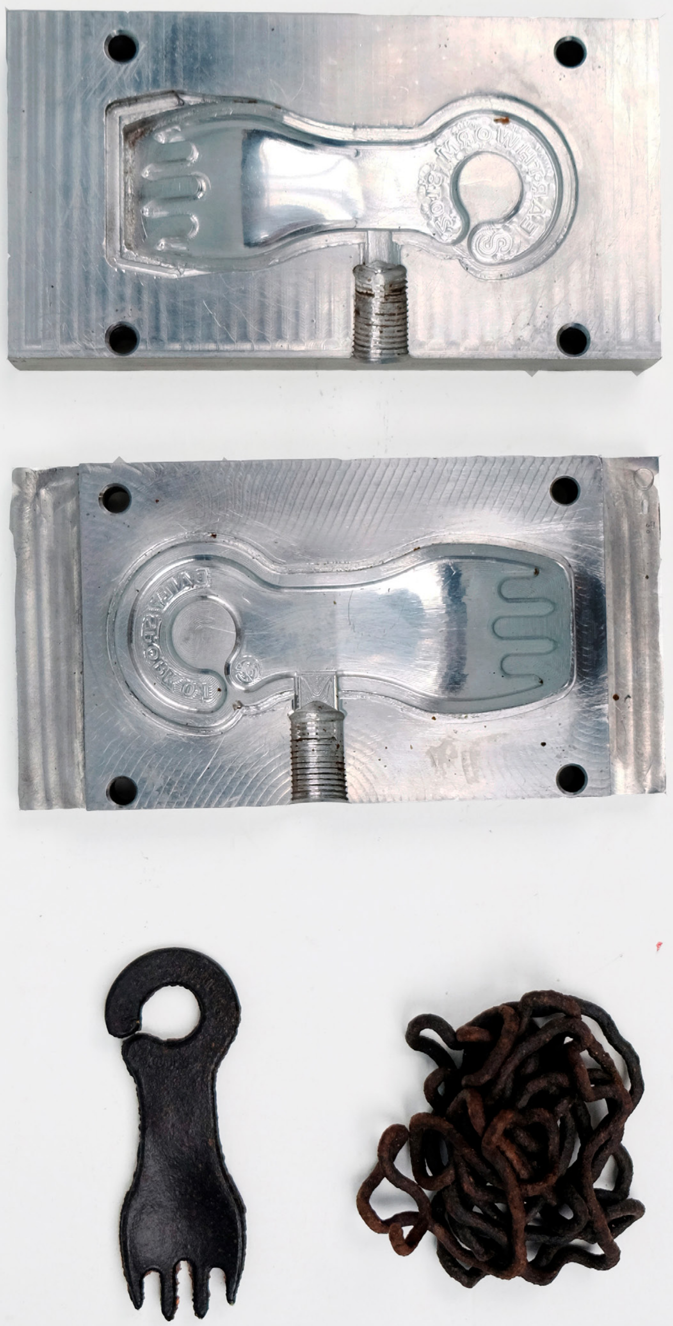
15.11.18 Tried 180 C in the tube. Failure, the mass got too thick and never made it to the mold. Cold pressed the leftovers in a 3-4mm layer - got hard when dried.
Goals: Less water, go back to 100 C in the tube.

20.11.18 Checked the time and amount. 60p+30w - 2 forks out of the amount (including the nozzle fill up). Takes 2 min to fill up the mold.
Pre-heated mold 180C - gives a lighter surface, not burnt. More pressure gives the evener surface. Shrinks a lot after drying; the one made with a cold mold shrank more.

Ground pieces

09.11.18 Tried dry ground pieces - ground by hand. Nice texture. Pieces don’t make it stronger. Leather: tried in the mold - similar to the previous; also tried pressing without mold and cooked in the oven a day later - less flexible, weak, cracks. Hard board: very brittle without additional starch. The one with starch stuck to metal and got destroyed, so the outcome is not relevant.

▲ *Figure 5. Extract from my notebook with recipes & processes. Some notes might be incomplete.*



Part 3. Process:

Extrusion

In the extrusion experiment, I set out to explore a different process and possibilities to work with another Precious Plastic machine. From the material properties perspective, the aim was to examine how potato peels would behave in the extrusion machine and in a more detailed mold. In order to save time, the presented aluminum mold was borrowed from Paul Dufour, Precious Plastic team member. Initially, this mold was designed and utilized for conventional plastic recycling.

Used equipment:	**Used materials:**
Extrusion machine — Aluminum mold (spork) — Oven — Scales	Potato peel powder — Potato peel flakes — Water

▲ *Extrusion machine by Dave Hakkens. Image 10.*

Extrusion Machine.
Extrusion is a process that produces a continuous thread of material. The machine contains a hopper and a barrel with a big screw inside. Along the barrel are four heating bands, that are connected to the electronic controllers, being split into two parts (nozzle and barrel). The first three elements compose the barrel part and are normally set at a lower temperature than the last nozzle part. The material is loaded into the hopper and carried by the screw towards the nozzle becoming molten by the heating elements and the mounting pressure. Then, it leaves through the nozzle being continuously extruded into a line. This normal extrusion process was followed in my experiments, using potato peel powder. The major difference from plastic extrusion, in this case, was the lower temperature rate.

Experiments: Milestones.

1. The first experiments started with failures. Since this was my first experience with the extrusion machine, I was not aware how exactly the speed affects gelatinization, and what would be optimal temperatures in the barrel and nozzle. As a result, with a medium speed, high temperature (250°C) made the peels cooked and stuck inside, while the attempt with a low temperature (50°C) resulted in a weak material with a rough splintering surface.

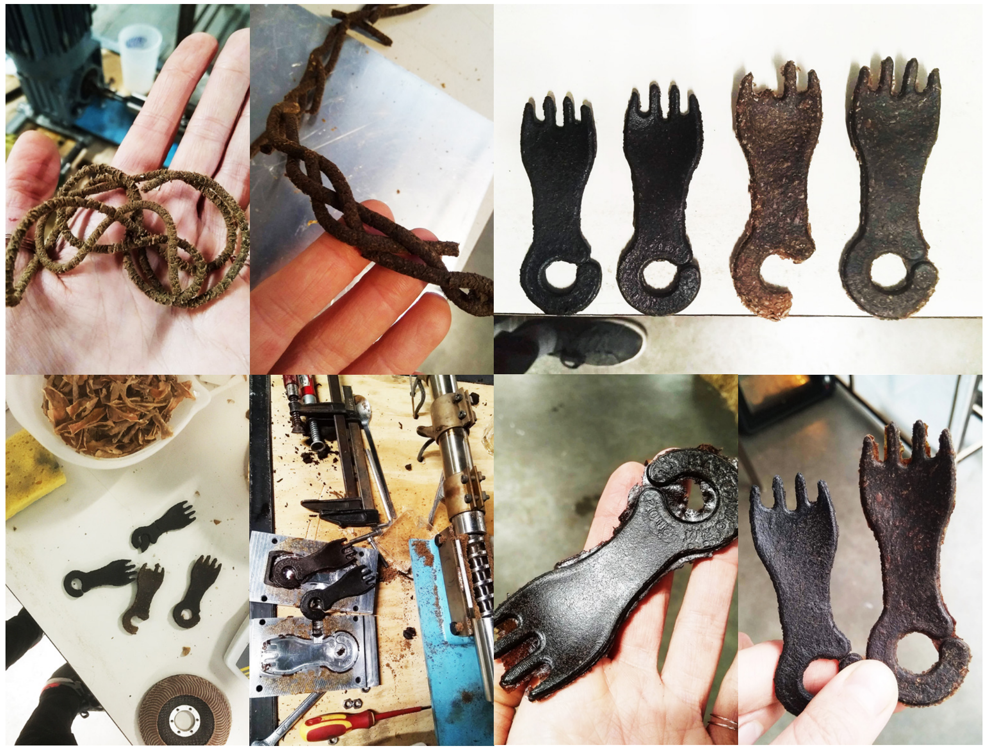
2. The next effort was more successful when I set the low speed and the temperature around 100°C. This resulted in a stronger and smoother thread. While the thread is still hot, the material is sticky, and it is possible to arrange it layer by layer. Hence, the 3D printing direction might be employed in possible future research. Both normal and layered threads are presented in the picture below.

▼ *Extruded potato peel mass. Normal and layered threads.*

3. In the first two extrusions into the mold, I utilized the temperature and speed from the previous attempt. In both cases, the nozzle temperature was 100°C, and the second one was extruded in a preheated mold. As a result, both samples appeared wet and slightly flexible and hardened within several days. The material was able to spread into the mold well, covering all the details. However, the sample extruded in the pre-heated mold obtained a smooth glossy surface, while the second one was rougher.

4. Since the previous samples still contained some moisture after being cooked, the next aim was to minimize it in order to achieve as dry and hard material as possible. In order to do this, two assumptions were made. First, with the same recipe, the temperature was raised to 180°C in the nozzle and 80°C in the barrel. The resulted mass thickened too fast and was stuck inside the extruder. Second, the temperature was set back to 100°C in the nozzle, but the water ratio was modified to be lower. The outcome sample was still wet; hence, the process requires further research on achieving more efficient moisture evaporation.

▼ *Extruded samples. Right: material shrinkage after drying.*



▲ *Extrusion process*

Observations & conclusions

Shrinkage. When the material dries completely, it becomes about 10% smaller, due to the water content that evaporates within several days. The sample final size is 90 x 32 mm, compared to the original 95 x 35 mm.

Pressure. More pressure allows for achieving a more sealed and strong surface — lack of pressure results in rougher and weaker samples.

Overheating. In the case of overheating, potato peels gelatinize too fast and become sticky. Hence, the material might get stuck inside the barrel, even when the speed is relatively high.

Mold preheating. It might be beneficial as it makes the material surface more sealed, which looks smooth and shiny. In addition to this, it finishes the cooking process to some extent, which reduces shrinkage. However, preheating temperature should not exceed 200°C, as it burns the material.

The Working Recipe.
The following instruction is the outcome knowledge of extrusion experiments. It is not considered as an accomplishment, but rather a reference for further development.

Ingredients	2/3 potato peels + 1/3 water *For two samples 95 mm x 35 mm it takes 60 g of peel powder and 30 ml of water. This amount is slightly extra since some of the material stays in the extruder nozzle.*
Temperature	Up to 100°C in the nozzle and 30°C — 50°C in the barrel *The temperature in the barrel should be mild. Otherwise, the material hardens and gets stuck inside.*
Optional	Mold preheating up to 180°C — 210°C *This step is optional. However, a preheated mold seals the surface, making it smoother.*
Extrusion	Low speed. The material reaches the nozzle within 4 min and fills up the mold within 2 min. *Settings may vary. However, with a high speed, the time is too short to cook the starch, so the material appears weak and crumbly.*
Outcome	The material is a little flexible but hardens while drying within several days. *The outcome is not fully dry due to the leftover moisture that evaporates slowly after opening the mold.*

Part 4. Concept:

Take-away Container

After exploring several processes and the according behavior of potato peels, I aimed for continuing the material investigation through the creation of an application concept. As assumed, the development of an actual product would serve as a means to gain new insights through the process, as well as a demonstrative and understandable example for further open source sharing.

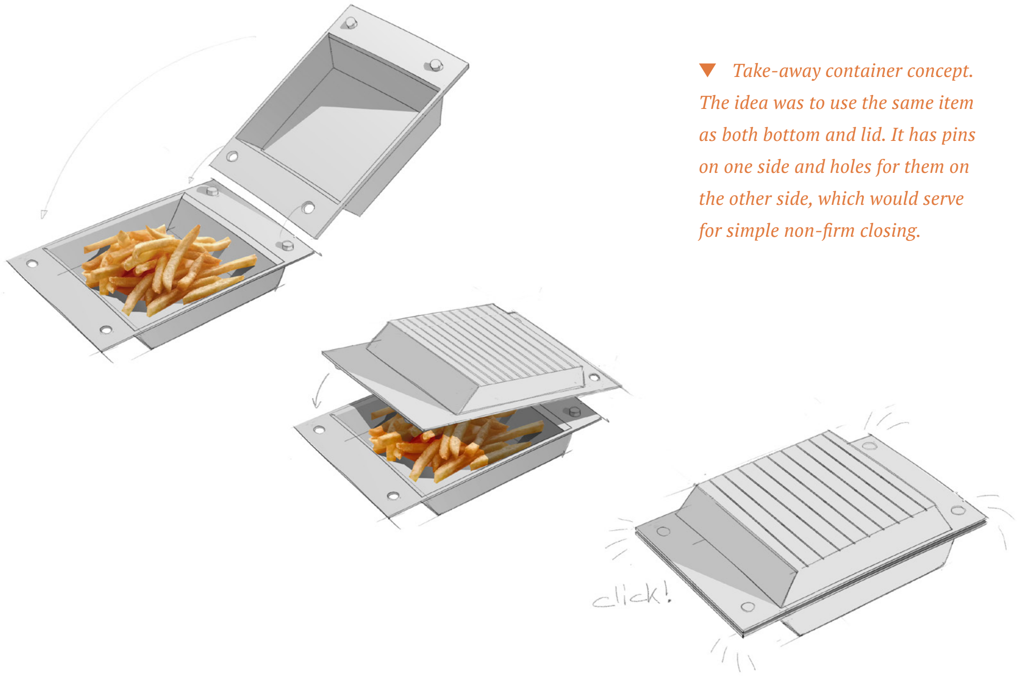
Used equipment:	**Used materials:**
Heatable mold (container)	Potato peel powder
Manual hydraulic press	Potato peel flakes
Scales	Water
Mold release	Recycled peels
	Industrial waste peels

Why a Take-Away Container?

As mentioned previously, one of the main goals of this thesis is addressing applications with a short life span, especially single-use items, which are designed to be disposed of immediately after usage. In the ideation of a potential application for potato peels, I took into account two aspects — the examined material properties, such as hardness and molding spreadability, and the most problematic single-use plastics, such as nutrient-contaminated food packaging.

Among these products, I decided to develop an alternative to polystyrene (also known as Styrofoam) packaging. This material is aging resistant and chemically stable which makes it non-degradable (Siyal et al., 2012). In addition to this, it contains toxic chemicals which might transfer into food and drinks (United Nations Environment Programme, 2018). Styrofoam is also problematic for recycling, since 98% of its structure is air which means high recycling cost.

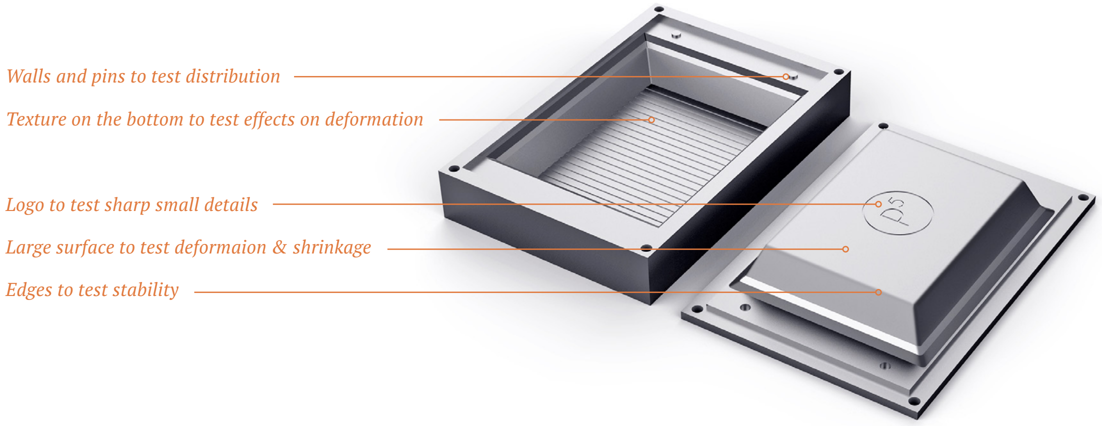
Hence, the proposed alternative packaging made of potato peels is assumed to address the issues mentioned above, being disposed of in compost with food.



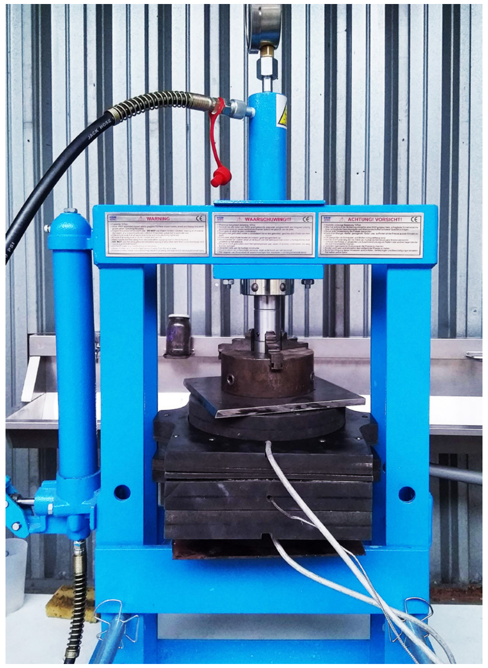
▼ *Take-away container concept. The idea was to use the same item as both bottom and lid. It has pins on one side and holes for them on the other side, which would serve for simple non-firm closing.*

Learning Tool

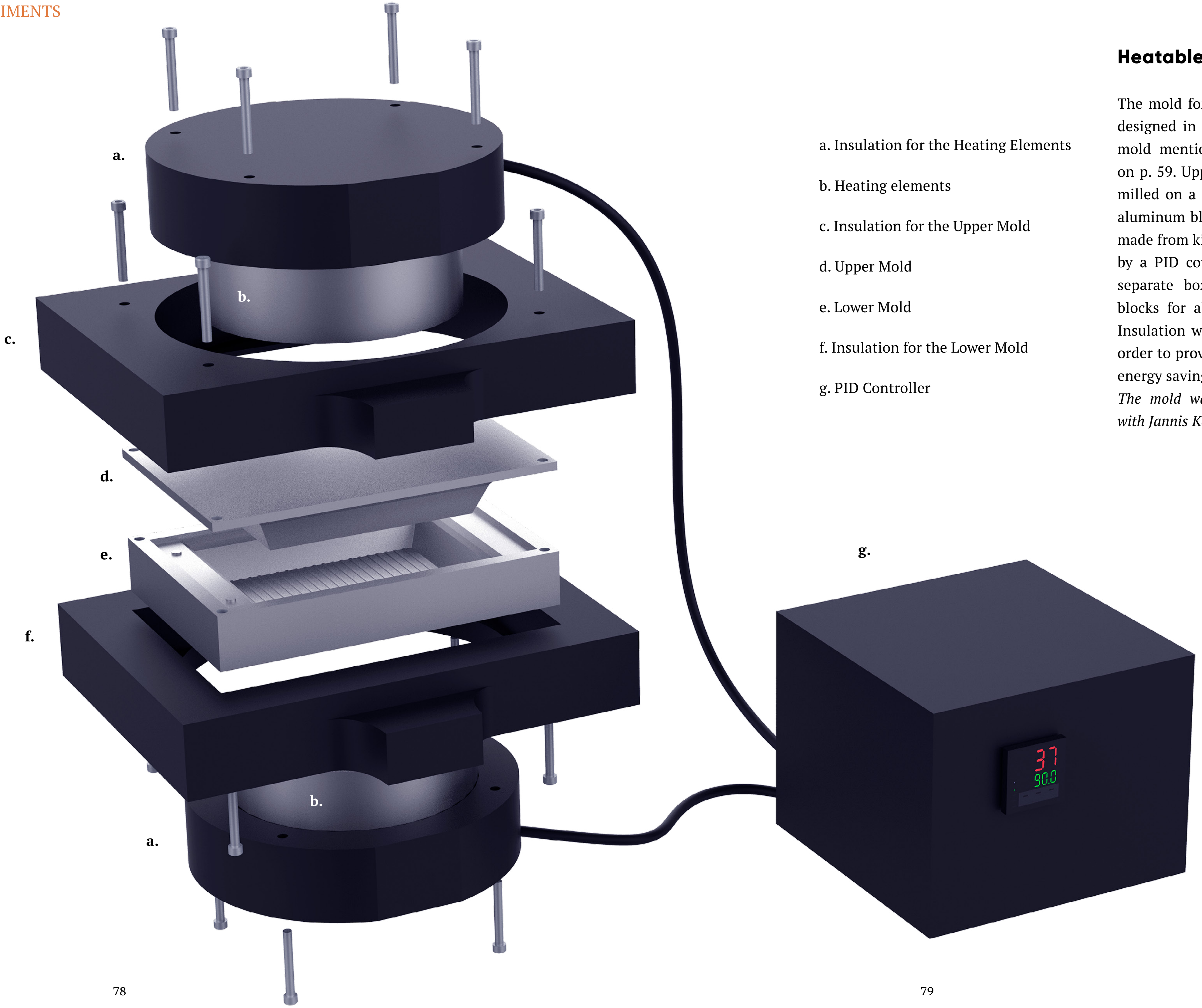
From the material investigation perspective, the step of mold making aimed for pushing the development of material characteristics further. Hence, the constructed mold is considered as a learning tool itself, with several aspects designed for examination and further knowledge sharing. These aspects are presented below.



▼ *Mold in the manual hydraulic press*



Compression in a Heatable Mold
The chosen process for producing a concept item was compression in a heatable mold. The decision was based on the previous experience, that heat and pressure are the major requirements for processing potato peels. Also, compared to the compression oven, this is more energy efficient.
The main components of the constructed mold are illustrated below on p. 76. The compression process is identical to one described on p. 59. The mold is placed in the manual hydraulic press and pressed at the required temperature under 5 -7 metric tons for the required time. Some recipe examples are presented in Figure 7 on p. 78 along with some photos of obtained samples on p. 79 and process on p. 80 - 81.



a. Insulation for the Heating Elements

b. Heating elements

c. Insulation for the Upper Mold

d. Upper Mold

e. Lower Mold

f. Insulation for the Lower Mold

g. PID Controller

Heatable Mold Layout.

The mold for the take-away container was designed in a similar way to the heatable mold mentioned in the previous chapter on p. 59. Upper and lower mold parts were milled on a CNC machine from a recycled aluminum block. The heating elements are made from kitchen hot plates and regulated by a PID controller which is located in a separate box. There are four insulation blocks for all heating metal components. Insulation was milled from MDF sheets in order to provide more efficient heating and energy saving.
The mold was constructed in co-operation with Jannis Kempkens and Friedrich Kegel.

◀ *Figure 6. Explosion scheme of the heatable mold for the take-away container concept.*

Dry peels from the kitchen

1. 125g of peels + 53g of water; pressed for 10 min at 90C; 6 tons. Mold release: olive oil
2. 110g of peels + 55g of water; pressed for 20 min at 85C (5 tons 3min + 7 tons 17 min)
3. 115g of peels + 50 g of water; pressed for 15 min at 85C
4. 110g of peels (fine powder) + 45g of water; pressed for 23 min at 70C
5. 110g of peels + 45g of water; pressed for 20 min at 85C (5 tons 2 min + 6.5 tons 18 min)
6. 110g of peels + 50 g of water; pressed for 10 min at 100C
7. 115g of peels + 50g of water; pressed for 20 min at 85C (5 tons 2 min + 7 tons 18 min). Mold release: rice bran oil
8. 120g of peels + 53g of water; pressed for 10 min at 90C; 6 tons. Mold release: olive oil
9. 115g of peels + 50g of water; pressed for 6 min at 95C
10. 110g of peels + 45g of water; pressed for 20 min at 85C (5 tons 2 min + 7 tons 18 min)
11. 125g of peels + 35g of water + 20g of beetroot juice; pressed for 10 min at 90C
12. 115g of peels + 50g of water; pressed for 14 min at 100C (5 tons 1.5 min + 7 12.5 min). Mold release: rice bran oil
13. 115g of peels + 50g of water; pressed for 7 min at 110C (5 tons 1.5 min + 7 tons 5.5 min). Mold release: rice bran oil - Failure
14. 115g of peels + 50g of water; pressed for 5 min at 100C (5 tons 2 min + 7 tons 3 min). Mold release: rice bran oil - Failure

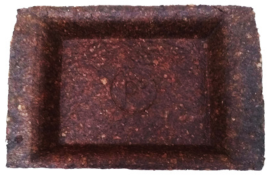
Recycled peels

15. 90g of peels + 20g of potato starch + 45g of water; pre-cooked in a pot, then pressed for 15 min at 85C
16. 95g of peels + 15g of potato starch + 45g of water; pressed for 20 min at 85C
17. 85g of peels + 35g of potato starch + 45g of water; pressed for 20 min at 85C (5 tons 2 min + 7 tons 18 min)
18. 85g of peels + 35g of potato starch + 50g of water; pressed for 20 min at 85C (5 tons 2 min + 7 tons 18 min)

Peels from Peka Kroef (industrial waste stream)

19. 175g of the mix (a bit moist); pressed for 6 min at 95C; 5 / 7 tons. Mold release: rice bran oil
20. 170g of the moist mix + 10g of beetroot juice; pressed for 6 min at 95C; 5 / 7 tons. Mold release: rice bran oil
21. 180g of the moist mix; pressed for 6 min at 95C; 5 / 7 tons. Mold release: baking spray
22. 130g of peels (burnt) + 50g of water; pressed for 7 min at 90C

▲ *Figure 7. Extract from my notebook with recipes & processes. Not in chronological order.*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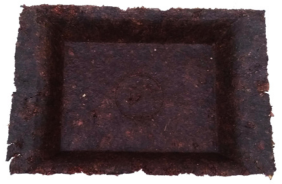
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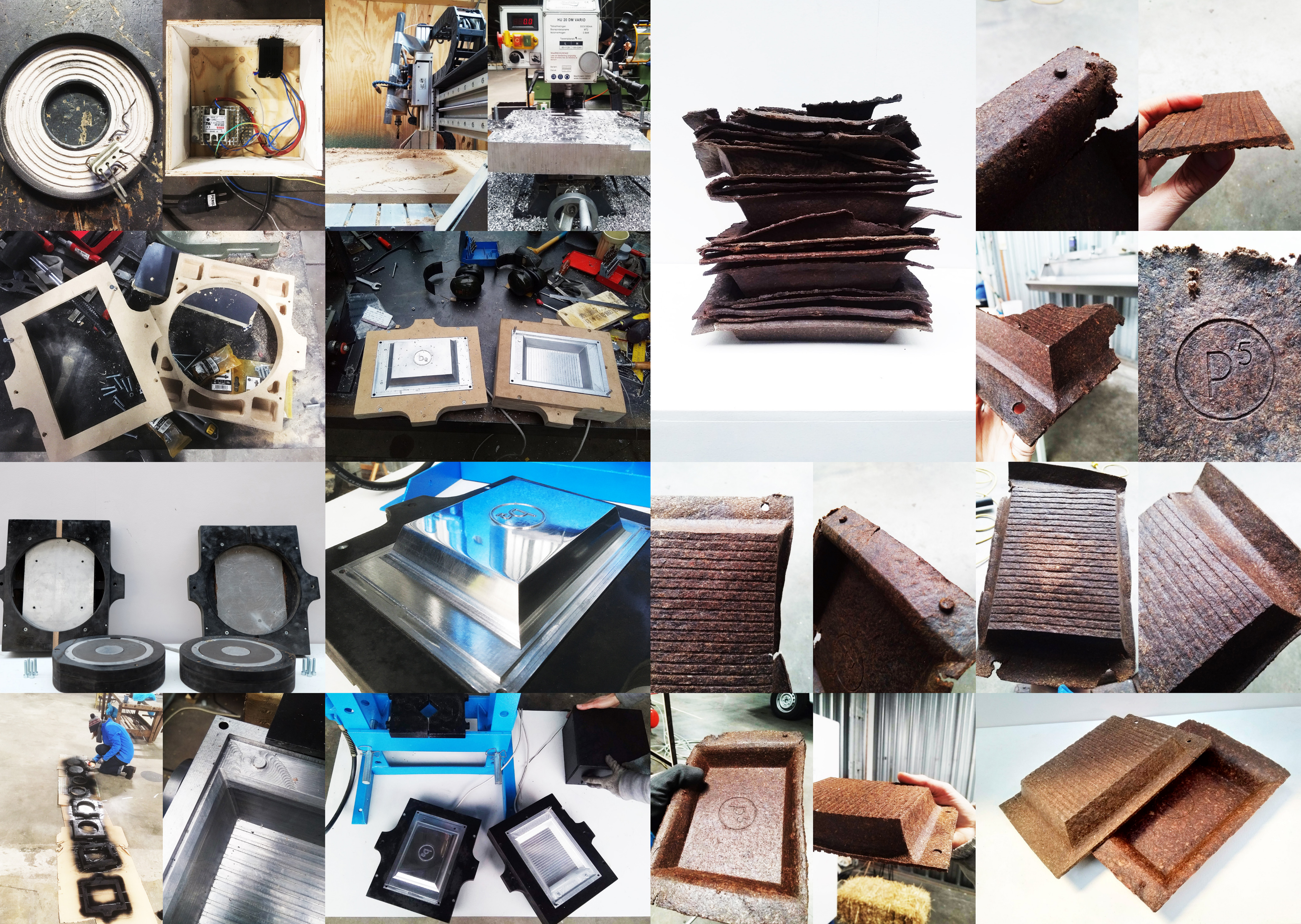
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Potato Peels as a Biomaterial.

This section provides a review of the essential material characteristics which were observed during the process of compression in the heatable mold. Some of these features were discovered in the previous processes and were either approved or pushed further. A number of these properties could be beneficially employed in products, whereas others should be taken into account and possibly improved.

Distribution.
The material has excellent distribution properties. When starch starts gelatinizing, the mass spreads efficiently over a mold. The water content ratio affects this process; hence, the increased water amount enhances the material spreadability. However, as resulted from conducted empirical research and background literature, the material can spread effectively even with a restricted water content of 30%.

The take-away container mold, utilized in this study, has steep walls and little pins protruded from the top. Nevertheless, the material fluently reached the top and spread into all parts of the mold in most of the samples. Such flexibility and viscosity enable to process this biomaterial with various machines, providing diverse molding possibilities.

▼ *Pins and holes on top.*

▶ *Sharp logo on the bottom.*

Sharp details.
Excellent distribution properties of potato peels enable to produce small details with both fine powder and bigger flakes. However, the pressure under 5 – 7 metric tons is required for covering all details and sealing the surface. The container mold has an imprinted logo on the bottom and a striped pattern on the outer side. Both of these details appeared very sharp and precise.

Shrinkage.
As mentioned previously in the extrusion process section, this biomaterial shrinkage is approximately 10% of its initial condition. One of the main goals of this research stage was to minimize the leftover water content in the outcome samples, which would allow for tackling both shrinkage and deformation issues. Two assumptions were tested: 1) a higher processing temperature within a shorter time, and 2) the minimum possible water ratio. However, these experiments did not provide any improvement. In the heatable mold process, even a slight temperature increase resulted in a strong stickiness which is elaborated below. In the case of reduced moisture component below 25 — 30%, the distribution property weakened considerably. Hence, further research on moisture evaporation is required.

▲ *The lower sample has extended edges, which made the walls more stable and less deformed.*

Deformation.
Material deformation occurs due to the moisture leftover content as pressed samples are a little moist and flexy. The water evaporates unevenly, and when the material hardens, larger surfaces without edge support are prone to bending and deformation.
In the take-away container, the side walls did not have enough support in the beginning and tended to deform significantly. This issue was fixed with the additional L-profile edge on the walls. In order to do this, the edges of the mold were extended by milling and welding.

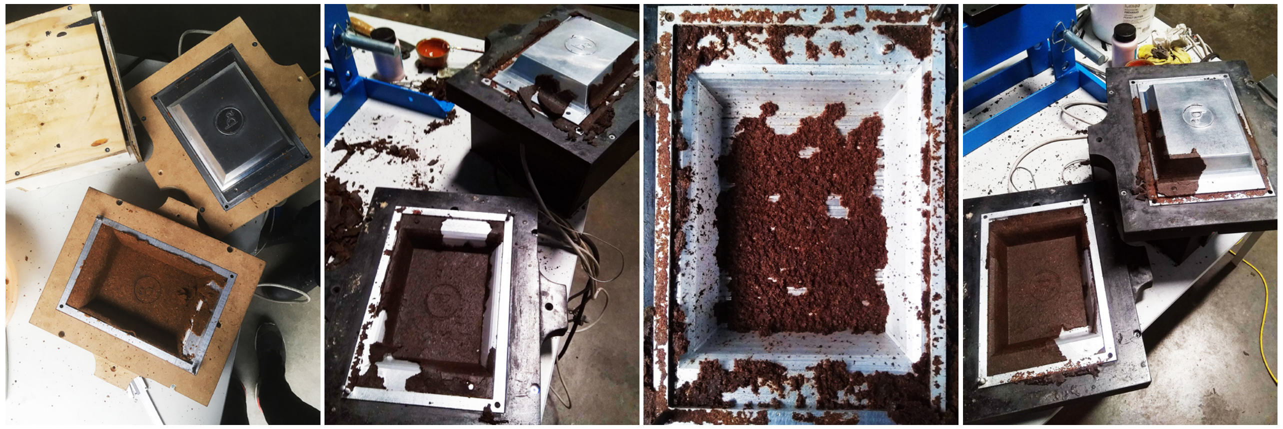
Stickiness.
Stickiness appeared to be the most unpredictable challenge of the experimental research stage. The material tended to stick to the mold partially or entirely in the majority of attempts in the process of compression in the heatable mold. In contrast, the mass was never stuck in the mold during other processes, such as extrusion molding or cold compression.

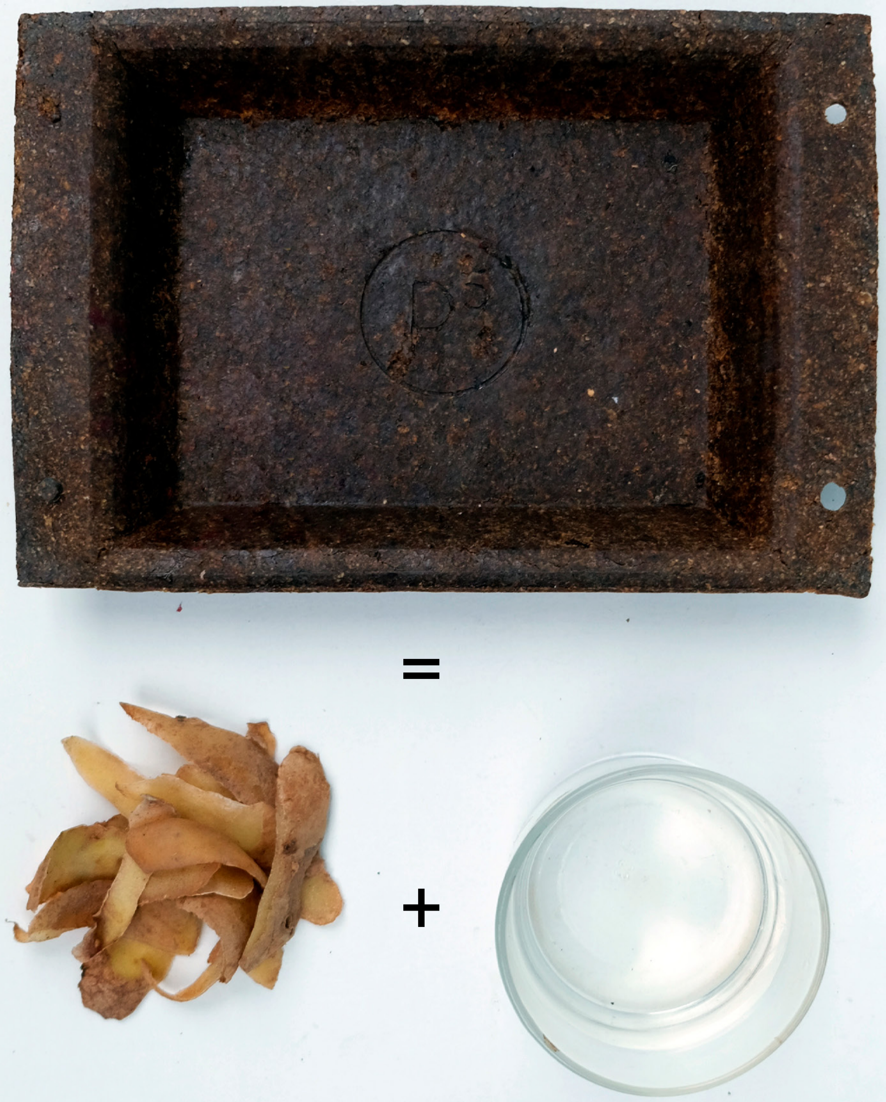
Within the time frame of this study, I managed to identify three main aspects that positively affect this issue. 1) The optimal temperature range is 75°C – 95°C. Overheating above this range leads to material stickiness most of the times. 2) Mold release should be applied on the mold surface first. Several vegetable oils, such as rice bran, sunflower, and olive oils, were tested at this stage. Further research into other lubricants would be beneficial. 3) Polishing and removing rough particles from the aluminum mold enables to obtain a smoother surface and make it less prone to stickiness. More thorough research into stickiness was beyond the time frame of this study; hence, this aspect requires further investigation.

Design of the mold.
The produced mold was a part of the material investigation process. Certain aspects in it were designed in order to examine biomaterial properties and push its development further. However, after the analysis of the process and the outcome samples, I outlined several elements which should have been designed differently.

Corners.
From the distribution perspective, the sharp corners of the mold demonstrated that this feature is achievable in potential applications, and potato peels are well approachable in increased complexity. However, due to the aforementioned stickiness, demolding was hard sometimes, and sharp corners were an additional detail to consider. Hence, a more optimal decision would have been a radial corner.
Pins & Edges.
The pins on the top, mentioned previously, should be designed differently. Their size is tiny, which makes them weak and easily breakable. The edges should be supported in order to prevent deformation of the object.

▼ *Stuck material is torn when opening the mold.*





The Working Recipe

The following instruction represents the most successful recipe from the experiments with the heatable mold. It is not considered as an accomplishment, but rather a reference for further development.

Ingredients	70% of potato peels + 30% of water *For a container 230 x 150 x 31 mm it takes 125 g of peel powder and 53 ml of water.*
Temperature	The mold is heated up to 90°C *The settings may vary — in general, lower temperature requires longer processing*
Mold release	Vegetable oil or other lubricant is applied on the mold surface *This step is a measure to reduce stickiness*
Press	10 min under 7 metric tons *If the pressure is too low, the surface appears weaker with multiple little cracks.*
Demolding	The pressure is released slowly *Fast pressure release might damage the surface due to the fast steam escape*

The following sixth chapter concludes the study with a discussion of the outcomes and the major observations from the empirical research. Then, it brings forth the limitations that affected this study and provides suggestions for potential further development. The chapter closes with a conclusion that summarizes the whole scope of conducted work and outlines the main reflections.

CONCLUSIONS

6

Discussion

The aim of this thesis was to examine and display the potential of biomaterials as an alternative to conventional plastics in order to contribute to the global shift towards more sustainable production and circular economy. This study is not a solid refined concept but rather a step towards a more conscious consumption approach and more sustainable thinking, with the intention to serve as an example of a way to convert underrated materials into a valuable resource. This main incentive included several supporting iterations.

The first step was to decide on one biosource among multiple options since thorough experimentation with other biomaterials was outside the scope and time frame of this thesis. The experiments on other materials were conducted only to a small extent at the earliest stage as one of the means to narrow down the research framing. Another tool employed at this stage was benchmarking of existing products as well as creating an overview of biosource categories. The categorization was partially based on studies by Brigham (2018) and Jeevahan et al. (2017). These steps led to the focus on by-products and waste streams, among which the chosen target material was potato peels.

Further investigation of potato peels enabled a determination of it as a potentially valuable raw resource, due to its low cost, abundance, and interesting material characteristics. Thus, the second step grasped the possibilities and features of the chosen biosource through empirical research, as well as a literature review on the properties of potato peels' major component — starch. The starch overview was based on studies by Zavareze & Dias (2011), Shrestha & Halley (2014), and Xie, Halley & Avérous (2012). The main tangible outcomes of the study were obtained at this stage. These include numerous material samples that represent different processing techniques, recipe variations, and operation complexity. The empirical research method allowed for the obtaining of quick results, both working or failing, which pushed further material development from initially weak crumbly samples to more stable stronger artifacts.

An application concept was introduced as part of the material exploration. The process of mold creation and working on the concept itself allowed for two main perspectives to approach the biomaterial from. First of all, employing design for the application ideation helps to identify possible directions of the material usage. In this regard, creative thinking is intertwined with the empirical material research when every iteration outcome is evaluated from the material properties perspective. This combination displays how these characteristics might be potentially employed in products, or what is lacking and should be improved. Secondly, keeping in mind that the goal of this study was to explore and showcase what the biomaterials are capable of, the mold itself can serve as a learning tool to explore and indicate new features of the materials.

With the created container mold the main intention was to increase the mold complexity to push and test the material behavior in elements such as small details, sharp edges, and steep form. The assumption on the capability of peels to successfully pass the «complexity test» was based on the results from previous experiments when the material proved its spreadability and flexibility of processing. However, in reality, the step appeared too large. Even though the process worked, and in the end, I got the containers, there were unexpected challenges, such as a strong stickiness, which required time and effort to be solved. In this regard, sharp edges and steep walls were an additional difficulty that slowed down the development. The drawn conclusion is that the increase in complexity should happen more gradually. It might be faster for the process to make two smaller iterations than a drastic one.

From the perspective of the material characteristics, the research demonstrated that potato peels might serve as a remarkable alternative biomaterial. In the scope of the uncomplicated technological process and basic recipes with minimum ingredients, the outcome properties are as follows:

1. Peels can produce sturdy hard boards. However, these are not as durable as conventional polymers; hence, would suit better in short-term applications.

2. Since potato peels contain a significant amount of starch, it does not require any additional binder. This feature enables the recipes to be kept simple and inexpensive. In addition to this, starch allows for various processing techniques to be employed, such as extrusion molding due to its high viscosity.

3. As a result of the effective spreadability of this biomaterial, the mass is able to cover small details and sharp corners.

4. Several features should be taken into account during the processing and when designing a mold. These include possible shrinkage and deformation, which are affected by water evaporation, and a possible stickiness within a higher temperature range.

5. The material does not demand high temperatures for processing, and the technique complexity level may vary. The processes described in this study, being stated as «low-tech,» still employed the equipment and machines from Precious Plastic. However, there is a certain flexibility for simplification, e.g., the material might be prepared in a cooking pot or pressed with an iron. Such flexibility allows for the material to be approached in different ways. However, the simplification approach serves only as a starting point to grasp the first impression of the biomaterial, since the outcome quality increases with the utilization of specific equipment, such as a hydraulic press.

Limitations

The biodegradation of the material was not tested in this study. However, given the fact that the recipes did not contain any inorganic ingredients and were processed with heat only, the assumption is that the samples should be able to degrade within 1 – 2 months, according to the pace of food biodegradation under controlled conditions (Zakarya et al., 2015).

Regarding the take-away container concept, there is no comparable data on if it affects the food taste in any way. Such testing was initially planned, but the experiments took longer than expected due to the issues faced during the process development. As assumed, there should be no considerable impact on the taste, since the surface is sealed with heat, but this theory needs further research.

Another limitation was mentioned earlier in this thesis, which is my limited knowledge of chemistry. As a designer, I am excited about the field and topic of biomaterials. However, in order to achieve faster material development, it would be beneficial to combine design and chemistry knowledge and skills. Hence, a collaboration with a chemical engineer would be advantageous for the research and would expand the learning experience from both disciplines.

After making the research outcomes open source, the feedback and comments on the forum were positive. Yet, I am not aware of any related further research conducted by others, as this aspect is not under my control and therefore limits my ability to assess the implementation accessibility of the processing instructions and recipes. A survey might have been a useful tool to gather such data, but this was beyond the time frame and scope of this study.

Future Research

In regards to biomaterials in general, future research is required to emphasize the potential value of other biosources within the food waste and by-products streams. Many of these biomaterials conceivably have valuable properties and could be sourced locally in many countries. The examples include but are not limited to onion peels, coffee grounds, corn cobs and leaves, and rice bran. However, since raw by-product resources are currently being utilized in some other application, such as animal feed or chemical extractions, further research is required on any possible negative impact on these applications in case of employing the resources as new value-added materials. A cost-effectiveness analysis would be also beneficial for the assessment of biomaterial potential in various applications.

Considering further development of potato peels, material treatment and processing should be studied. The assumption is that other types of treatments which are normally employed for pure starch might potentially improve the properties of potato peels. In addition to this, further research into such aspects as material stickiness and deformation might be beneficial.

In consideration of knowledge sharing, a workshop to involve people in material creation might be a suitable tool. An example of this is Materiom. In the organized workshops, they present their samples and bioplastic recipes and cook them together with the participants.

Conclusion

This study investigated and demonstrated the material properties of potato peels as a potential alternative to conventional plastic. Several processing techniques were examined — extrusion, compression, and compression in a heatable mold. The tangible outcomes of these experiments included various samples that were prepared with different ingredient ratios and processing settings. As background support for the experiments, literature about starch and its modification techniques was studied. The study employed an uncomplicated material treatment and a minimum of ingredients in order to make the processes accessible and replicable. As part of the material exploration, an application concept was represented, as well as its development which included mold making and further empirical research. The outcome knowledge with descriptions, instructions, and recipes is open source and available on the forum of the plastic recycling community.

The obtained material is hard and sturdy when dry. The starch content of potato peels serves as a binder, which allows for the recipe to be kept simple, without any additional binding agent. During the material processing, the starch makes the mass viscous and flexible, which enables various techniques to be applied, including extrusion molding or compression molding, and allows for sharp edges and small details to be covered.

Considering the application possibilities of potato peels studied within the scope of this uncomplicated treatment, it is not suggested to utilize them for long-term household or industrial products. The outcome material is less durable than conventional polymers and obtains a potentially rapid biodegradability. Hence, single-use items are the most suitable application for it, as assumed at the beginning of this study. In regards to the biodegradability of different materials within the global consumption, biodegradable and compostable bioplastics are not able to serve as a simple solution to the global waste issue. They are rather a part of the system that also includes recycling, reusing, and efficient waste management. Nevertheless, these kinds of materials are the most appropriate in specific short-term applications, where biodegradability and compostability are among the core properties.

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Images

The images which are not specified, are the original content.
The exceptions are listed below.

Image 01. Dave Hakkens, *Precious Plastic*. https://preciousplastic.com

Image 02. Smith, H. & Dean, R. T. (2009). *A model of creative arts and research processes: the iterative cyclic web of practice-led research and research-led practice.* Edinburgh: Edinburgh University Press.

Image 03. European Bioplastics. Retrieved from https://www.european-bioplastics.org/bioplastics/

Image 04. Evoware, *Seaweed-based packaging.* Retrieved from http://www.evoware.id/

Image 05. Biotrem. Retrieved from http://biotrem.eu/

Image 06. Ecovative design, Retrieved from https://www.timesunion.com/business/article/Troy-company-creates-leather-like-material-made-12840393.php

Image 07. Chip[s] Board. Retrieved from https://www.dezeen.com/2018/12/12/rowan-minkley-robert-nicoll-recycle-potato-peelings-mdf-substitute/

Image 08. Materiom. Retrieved from https://materiom.org

Image 09. Dave Hakkens, *Compression oven.* Retrieved from https://preciousplastic.com

Image 10. Dave Hakkens, *Extrusion machine*. Retrieved from https://preciousplastic.com

Photos on p. 64, 71, 72, 86, 88 were taken by Sera P. Thomsen.

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