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A Biodegradable Alternative to the Single-Use Cup

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Submitted to:

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1.0 Abstract

One hundred billion single-use cups are sent to landfills annually in the United States. Their production, usage, and disposal cause deforestation, pollution, and human health problems. Attempts have been made to produce more environmentally friendly tableware, however, these options are frequently not economically or logistically viable. This project strived to develop a single-use cup that meets the market need while remaining biodegradable and sustainably sourced. A financial and market analysis demonstrates the cup's ability to enter the industry.

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2.0 Introduction

With the growing popularity of sustainability, many companies have begun using environmentally friendly materials. This is particularly significant for the disposable tableware market. Most plastic utensils, paper plates, and styrofoam carrying containers are used once for a few hours and then left in a landfill for hundreds of years before they degrade. Efforts have been made in recent years to create single-use tableware that biodegrades in a shorter time frame. Despite their widespread use, single-use cups have not received an environmentally conscious upgrade. This project focused on creating a fully biodegradable single-use cup. The final product consists of agar, hemp, and other natural ingredients coated with wax. This report presents the production process of the product as well as an overview of the engineering design that utilized an axiomatic design process to develop the product. Additionally, a series of experimental tests are outlined that demonstrate that the product has potential to become comparable to other similar products on the market. Furthermore, a financial and market analysis was conducted to display the single-use cup industry and a biodegradable cup's place in it. The creation of this fully biodegradable cup makes further strides in the ever-present goal of developing sustainable single-use tableware and has applications beyond the initial goal.

3.0 General Problem Statement

Single-use tableware is commonly used around the world. This tableware is most often made out of plastic, paper, and expanded polystyrene (styrofoam). Each of these materials is damaging to the environment in multiple ways. Hundreds of years are required before plastic is fully degraded. Paper cups lead to deforestation and their waterproof coatings are sourced from petroleum and do not degrade. Finally, styrofoam leaks harmful chemicals into the food it touches and the environment once it is disposed. These mainstream options are not sustainable. Recently, there has been a push to limit the use of disposable cups. Efforts have been made to incentivize consumers to opt out of single-use options. Several dining locations like Starbucks offer discounts to those who provide their own reusable cups. However, only 1.6% of Starbucks coffee drinkers take advantage of this initiative (Starbucks, n.d.). Market evidence shows that there is consumer reliance and demand for single-use cups. However, there is an equal need to mitigate the disposable cup's negative impact on the ecosystem. An environmentally friendly single-use cup is necessary.

4.0 Background

4.1 Mainstream Commercial Options

The three most common types of disposable cups are those made out of paper, styrofoam, and plastic (What, 2018). Figure 1 compares the three main single-use cups' length of storage, use, and degradation. As shown, each of the mainstream options has a much shorter use time compared to their respective degradation time. All three of these cups negatively impact the environment and human health in major ways.

Figure 1: Shelf Life, Use Time, Degradation Time for Cup Options

4.1.1 Paper Cups

Paper cups are created from the fresh pulp of lumber, requiring the destruction of trees in the production process (Starbucks, 2018). 20 million trees are cut down annually for the production of paper cups, as most cups are made from virgin paper (Steely's Drinkware, 2013). Despite being made out of a naturally biodegradable material, paper cups continue to harm the environment in the post usage stage. For every four paper cups discarded, one pound of CO_2 emissions is created, and in the U.S. alone, 58 billion paper cups are thrown away annually (Steely's Drinkware, 2013). In order to remain waterproof, the cups are lined with polyethylene, a type of plastic that is not biodegradable or compostable. This means that the entire cup is unable to be composted or broken down by the environment. Additionally, because of their plastic coating and the fact that they are less resilient to foreign contaminants, paper cups are often unable to be recycled (Steely's Drinkware, 2013).

4.1.2 Styrofoam Cups

In the US alone, 25 billion styrofoam cups are used and discarded annually (Steely's Drinkware, n.d.). Styrofoam cups are made from a non-biodegradable, petroleum based plastic that cannot be recycled and is estimated to last between 500 and one million years before fully breaking down depending on the external conditions (Le Guern, 2018). Additionally, polystyrene, the main component of styrofoam, leaks an endocrine disruptor called leaches styrene when it comes into contact with oily or heated materials. This disruptor can cause long term health problems affecting the reproductive and nervous systems of its users (Le Guern, 2018). Significant migration of this chemical occurs any time styrofoam cups are used for hot liquids. Furthermore, approximately 90 toxic and hazardous chemicals are produced when cups are incinerated by disposal companies (Steely's Drinkware, n.d.). Despite this, styrofoam continues to be a mainstream material choice for single use cups.

4.1.3 Plastic Cups

Plastic cups, while less destructive to human health than their styrofoam counterpart, are the most common type of single-use cup and still have many known issues associated with them. As of 2018, the world population uses 500 billion plastic cups a year (Fact, 2018). Single use plastics are divided into two categories, plastics that are malleable when reheated, called thermoplastics and plastics that once set with heat, remain rigid, called thermosets (Giacovelli, 2018). Neither thermoplastics nor thermosets break down naturally in the environment or with commercial composting. About 80% of plastic products ever produced are discarded in the environment (Giacovelli, 2018). This results in plastic occupying 30% of all landfill space (Steely's Drinkware, 2013).

Plastic cups are sometimes advertised as being recyclable or even compostable, but due to human error, this frequently does not happen (Reality, 2015). In fact, only about 9% of plastic products get recycled (Giacovelli, 2018). A description of the difference between compostable and biodegradable products is shown in Figure 2. Despite these obvious problems, the versatility and low cost of plastic perpetuates its reliance in comparison to eco-friendly alternatives. Plastics tend to be "lightweight, hygienic and resistant" over long periods of time, making them favorable for food storage and other packaging needs (Giacovelli, 2018). These properties become especially important for containing and transporting liquids. A cup needs to be able to preserve liquids for an extended period of time, protect contents from outside contaminants, be transportable, and display information, making single-use plastic cups the mainstay of the disposable cup market (Harvey, 2018).

Even the plastics that are considered "safer plastics," such as bioplastics, have many negative impacts on the environment. The plastic still takes many years to fully break down, and when it does, it can be ingested by wildlife in the form of microplastics and toxins, which are both extremely harmful to the ecosystems (Le Guern, 2018).Without alternatives that meet the needs currently fulfilled by plastic options, it will continue to remain the dominant option, despite its negative environmental impact.

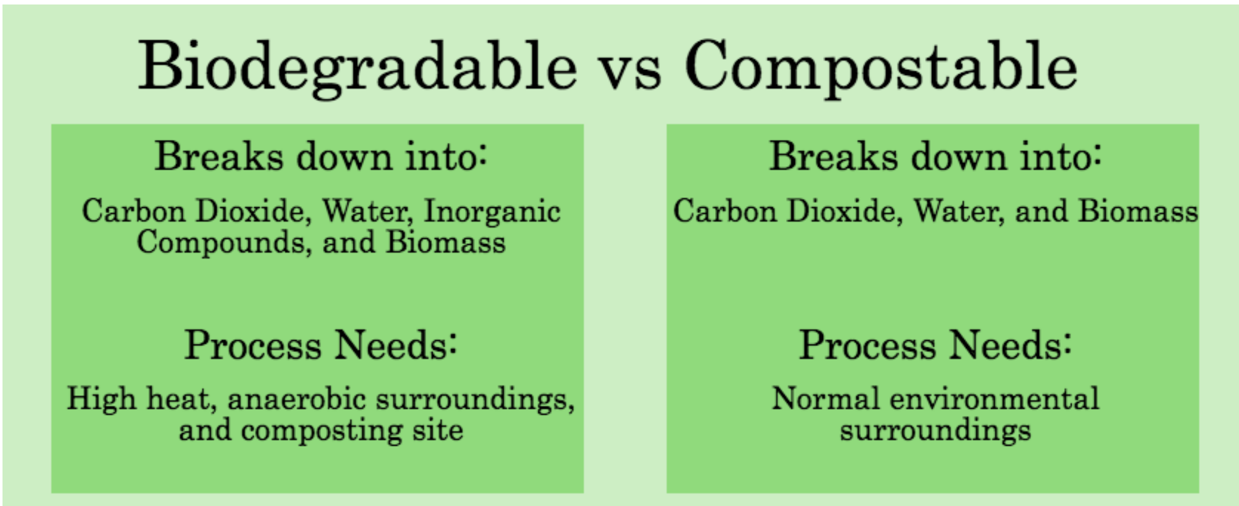


Figure 2: Compostable vs. Biodegradable (LeGuern, 2018)

4.2 Environmentally Friendly Alternatives

In an effort to eliminate the use of paper, styrofoam, and plastic from the single-use tableware industry, other more sustainable options have been innovated for the market. However, they each have a reason that they fail at replacing the single-use cup market. Table 1 compares these sustainable options versus paper, styrofoam, and plastic, highlighting key advantages and disadvantages.

Table 1: Current Alternatives

	Sustainable Source	Biodegradable	Easily Stored	Cup-Shaped	Resists Heat	Resists Moisture
Paper			X	X	X	X
Styrofoam			X	X	X	X
Plastic			X	X		X
PLA	X		X	X	X	X
Sugar Cane	X	X	X		X	
Bamboo	X	X			X	X
Palm Leaves	X	X	X		X	X
BAKEYS	X	X				
BioTrem	X	X	X	X	X	

4.2.1 Polylactic Acid (PLA)

Tableware made of Polylactic Acid (PLA) plastic, shown in Figure 3, is commonly advertised as being a sustainable alternative. PLA is a hard material that is both heat and moisture resistant. Despite this resilience, PLA is made from corn byproducts and presented as compostable. However, this is misleading to consumers, as PLA is not capable of breaking down on its own in normal conditions. PLA, which is formed using injection molding, needs extreme heat and specific conditions provided at specialized recycling facilities to decompose (WorldCentric, n.d.). These facilities have to be equipped with the technology to recycle such plastics, but are often not locally available to the average consumer. These factors lead most PLA products to not be properly recycled and instead sent to landfills.

Figure 3: PLA Cutlery (Compostable, n.d.)

4.2.2 Sugar Cane

Sugarcane is a byproduct of the sugar production industry and is often discarded after necessary components are collected. Sugarcane is biodegradable and decomposes in three to six months (How Sugarcane, 2017). To create tableware out of sugarcane, the fibers are mixed together and heat-pressed into the desired shape. These plates do not require any external coating because they are not intended to be in contact with a large amount of liquid for an extended period of time (How Sugarcane, 2017). Sugarcane plates can be seen in Figure 4. Cups made from sugarcane, however, have the same petroleum-based polyethylene coating as standard paper cups and thus are not an ideal solution.

Figure 4: Sugarcane Based Plates (How Sugarcane, 2017)

4.2.3 Bamboo

Bamboo is another alternative biodegradable material on the market. Plates, bowls, and cutlery can be made with bamboo, and it is very durable as it is a wooden material. In order to create plates shown in Figure 5, bamboo is sheathed, boiled, then pressed and bonded together with an eco-friendly adhesive (How Sugarcane, 2017). Bamboo cutlery is formed from a single piece of raw material without using adhesives. Due to the way the plates are formed, large curved shapes, such as cups, are difficult to manufacture. Only small curves such as at the end of plates are possible. Bamboo both grows and breaks down quickly, and in a mild climate, it will break down in under 6 months. This makes the plate biodegrade rapidly, however its shelf life is limited.

Figure 5: Bamboo Plates (CiboWares, n.d.)

4.2.4 Palm Leaves

Palm leaves are commonly used in the manufacturing of biodegradable plates. Areca palm leaves are the most common leaves in use due to their size, stability, and natural water resistance. The naturally shedding palm leaves are collected, cleaned, dried, stretched, and heat pressed into shape (How Sugarcane, 2017). Similar to the bamboo tableware, this process is effective for flat tableware like plates shown in Figure 6, but is not as easily applied to curved forms such as cups or bowls.

Figure 6: Palm Leaf Plate (CiboWares, n.d.)

4.2.5 BAKEYS

There are also several edible alternatives to traditional single-use tableware that are on the market by companies such as BAKEYS™. Based in India, BAKEYS produces grain based tableware shown in Figure 7. This is made from a combination of flours, water, and sorghum (a variety of grain) . Due to its composition, it is susceptible to breaking down when it comes into contact with any liquid for longer than 10 minutes. When left to naturally decompose, they break down in under a week (3-7 days) (BAKEYS, n.d.). While this property aids in decomposition, it compromises the product if it is exposed to moisture before intended use. Its fragility makes airtight storage crucial to its functionality. BAKEYS can also break easily due to their brittle structure.

Figure 7: BAKEYS Spoons (Welcome, n.d.)

4.2.6 BioTrem

A similar edible grain based company is BioTrem™ which makes a wheat bran product shown in Figure 8. These bran products break down in just 30 days. Similar to the palm leaf plate manufacturing, bran tableware is created via heat pressing the material into the desired shape (BioTrem, 2016). BioTrem is made from wheat so it does not resist moisture for any significant amount of time.

Figure 8: BioTrem Plates (BioTrem, 2016)

5.0 Research and Development

The process for designing the final production of the single-use cup solution is discussed in this chapter. The steps to determine the required features of the cup are enumerated below followed by the considerations, experimentations, and ultimate choices that fulfill each of those respective features. The graphic in Figure 9 shows the life cycle of the product that was determined using the design methods.

Figure 9: Life Cycle

5.1 Identifying Design Parameters

An axiomatic design process was employed to fully understand the design elements necessary to creating a cup. Axiomatic design was developed by Dr. Suh Nam Pyo. This process involved the development of functional requirements (FRs) for the cup. To obtain these FRs, a comprehensive decomposition of the functions of a cup was created. A decomposition involves creating wide requirements and then exploring the sub-requirements of those FRs. This process is repeated until all specific aspects of the design are found. The decomposition was done by analyzing the different basic functions of a single-use cup and assigning measurable requirements that must be fulfilled. The final functional requirements are outlined in Table 2 below.

Table 2: Functional Requirements

Functional Requirements
FR0: Equip individuals with a single-use biodegradable cup
FR1: Create material for tableware
FR1.1: Identify a biodegradable material
FR1.1.1: Identify material that decomposes after use
FR1.1.2: Identify a nontoxic material
FR1.2: Create material that will maintain its structural functionality
FR1.2.1: Create material that maintains structural functionality for entire use
FR1.2.1.1: Choose material that maintains structural functionality when wet
FR1.2.1.2: Choose material able to withstand hot temperatures
FR1.2.1.3: Choose material able to withstand cold temperatures
FR1.2.2: Create material that will maintain structure after being in storage
FR1.3: Eliminate any taste altering effects of material
FR2: Create container for liquids
FR2.1: Design container to hold volume of liquid
FR2.2: Design container to support mass of liquid
FR2.3: Design watertight container

Once the functional requirements were established, they were translated into design parameters (DPs) that specified the method for accomplishing each requirement. The FRs and their corresponding DPs are shown in Table 3.

Table 3: Functional Requirements and Design Parameters

Functional Requirements	Design Parameters
FR0: Equip individuals with a single-use biodegradable cup	DP0: A cup that is biodegradable
FR1: Create material for tableware	DP1: Material for tableware
FR1.1: Identify a biodegradable material	DP1.1: Material that is biodegradable
FR1.1.1: Identify material that decomposes after use	DP1.1.1: Material that decomposes
FR1.1.2: Identify a nontoxic material	DP1.1.2: Material that is nontoxic
FR1.2: Create material that will maintain its structural functionality	DP1.2: Material that maintains its shape
FR1.2.1: Create material that maintains structural functionality for entire use	DP1.2.1: Material that maintains structural functionality for entire use
FR1.2.1.1: Choose material that maintains structural functionality when wet	DP1.2.1.1: Material resilient to wetness
FR1.2.1.2: Choose material able to withstand hot temperatures	DP1.2.1.2: Material resilient to hot temperatures
FR1.2.1.3: Choose material able to withstand cold temperatures	DP1.2.1.3: Material resilient to cold temperatures
FR1.2.2: Create material that will maintain structure after being in storage	DP1.2.2: Material that maintains structure in storage
FR1.3: Eliminate any taste altering effects of material	DP1.3: Material that does not alter taste of food
FR2: Create container for liquids	DP2: Container for liquids
FR2.1: Design container to hold volume of liquid	DP2.1: Container to hold volume of liquid
FR2.2: Design container to support mass of liquid	DP2.2: Container to support mass of liquid
FR2.3: Design watertight container	DP2.3: Container that is watertight

Several of the design parameters could only be achieved in a way that directly contradicted another parameter. These couples are shown in the matrix in Table 4, made using Axiomatic Design Solutions' Acclaro software. This matrix lists FRs and DPs on each axis. Any time a DP adjustment would affect an FR, an X is placed in the corresponding cell. The red cells indicate an FR and DP that are coupled because of the conflicting design. The concept of a biodegradable cup is contradictory. It is created with the purpose of breaking down, however, it must maintain functionality until and throughout its intended use.

Table 4: Coupling Matrix

	DP0: A cup that is biodegradable	DP1: Material for tableware	DP1.1: Material that is biodegradable	DP1.1.1: Material that decomposes	DP1.1.2: Material that is nontoxic	DP1.2: Material that maintains its shape	DP1.2.1: Material that maintains structural functionality for entire use	DP1.2.1.1: Material resilient to wetness	DP1.2.1.2: Material resilient to hot temperatures	DP1.2.1.3: Material resilient to cold temperatures	DP1.2.2: Material that maintains structure in storage	DP1.3: Material that does not alter taste of food	DP2: Container for liquids	DP2.1: Container to hold volume of liquid	DP2.2: Container to support mass of liquid	DP2.3: Container that is watertight
FR0: Equip individuals with a single-use biodegradable cup	O															
FR1: Create material for tableware		X														
FR1.1: Identify a biodegradable material			X			X	X	X	X	X	X					
FR1.1.1: Identify material that decomposes after use				X	X	X	X	X	X	X	X					
FR1.1.2: Identify a nontoxic material				X	X			X	X	X	X					
FR1.2: Create material that will maintain its structural functionality			X	X		X										
FR1.2.1: Create material that maintains structural functionality for entire use			X	X			X									
FR1.2.1.1: Choose material that maintains structural functionality when wet			X	X				X								
FR1.2.1.2: Choose material able to withstand hot temperatures			X	X					X							
FR1.2.1.3: Choose material able to withstand cold temperatures			X							X						
FR1.2.2: Create material that will maintain structure after being in storage			X	X							X					
FR1.3: Eliminate any taste altering effects of material			X								X	X				
FR2: Create container for liquids													X			
FR2.1: Design container to hold volume of liquid														X		
FR2.2: Design container to support mass of liquid															X	
FR2.3: Design watertight container																X

The couples that revealed themselves in the matrix were addressed with two methods. First, similar design parameters that would have to be fulfilled simultaneously were grouped into a broader parameter. For example, designing a decomposing material that is also non-toxic were both addressed at the same time since they are heavily influenced by each other. The second method to easing the coupling was establishing a logical order that allowed for each design parameter to be fulfilled while not affecting the previous design parameters. For example, one of the requirements for storability was to prevent mold growth. The solution to that was to use a mold preventative in the recipe. However, the next design parameter was to eliminate any taste altering substances; therefore, the selected mold preventative needed to be replaced since it was very odorous. The order allowed for a design process that met requirements without affecting past parameters. Using the previous two methods, a more concise list of broad parameters was created from the design parameters. The correlation of these broad parameters to DPs is shown below in Table 5.

Table 5: Broad Design Requirements vs. Original Design Parameters

Broad Parameter	**Design Parameter**
A non-toxic biodegradable material	1. A cup that is biodegradable
	1.1. Material for tableware
	1.1.1. Material that decomposes
	1.1.2. Material that is not toxic
A structural material	1.2 Material that maintains its shape
	1.2.1 Material that maintains structural functionality for duration of use
	1.2.1.1. Material resilient to wetness
	1.2.1.2. Material resilient to hot temperatures
	1.2.1.3. Material resilient to cold temperatures
A storable material	1.2.2. Material that maintains structure in storage
A material that does not impact taste	1.3. Material that does not alter the taste of food
A cup-shaped material	2. Container for liquids
	2.1. Container to hold volume of liquid
	2.2. Container to support mass of liquid
A waterproof cup	2.3. Container that is watertight

A structured design process was developed based on the parameters develop from the design decomposition. The six broad parameters from Table 5 are compiled again in Figure 10 in order. They were accomplished one by one until the final product was made.

Figure 10: Broad Design Parameters

Every decision that fulfilled a specific design parameter was required to simultaneously fulfill all previous design parameters. The end result was a functional cup that is fully biodegradable and made out of non-toxic materials.

5.2 Design Process

A cup was designed using the design parameters established in Section 5.1. The design process was iterative, fulfilling each design using a series of tests and experiments. Below, each design parameter is discussed in terms of its goal. The experimental methods that were employed to meet that goal are then outlined, followed by a discussion of the results of the testing. Using the information from the results, the production process was developed further. A full and final production process procedure of the final recipe and cup design is located in Appendix B. Ratios of ingredients are shown in Appendix C for the production of different amounts of the final material.

5.2.1 A Non-toxic Biodegradable Material

Creating a non-toxic, biodegradable material fulfills Design Parameter 1.1 and all of its sub-requirements. It is the logical first step because a material is required to physically make a cup, and the primary objective of the product is to be biodegradable. The design parameter's primary function was to establish a base for a composite material that will be developed over the rest of the design process. Once this was complete, the other parameters could be fulfilled iteratively, allowing the final product to be environmentally friendly by degrading naturally into non-toxic components.

5.2.1.1 Design Parameter 1 Initial Steps

Seven biodegradable materials were initially identified for this study. These biodegradable materials included individual substances as well as recipes that combined different non-toxic or food grade materials. These options were discovered through research from "do-it-yourself" websites, other biodegradable products, and culinary sources.

The "do-it-yourself" research yielded several different homemade glue recipes that were food grade and therefore biodegradable. The goal of exploring glues was to discover a way to bond materials together and waterproof them. Only waterproof glues were considered because the final product would be containing liquids. The first glue was made from a recipe of gelatin, water, and milk (11 Recipes, 2016). The use of milk led to the pursuit of a second waterproof glue recipe since the milk could spoil over time. The second recipe consisted of gelatin, water, and a bonding agent (11 Recipes, 2016).

The second category of options were other biodegradable products. Corn products are used in many different environmentally friendly applications, creating corn husks as a waste product. These husks were tested to observe their characteristics, because utilizing a material that was already a waste product would further increase the environmental benefit of the product. Similarly, leaves from local trees were tested since they are both biodegradable and bountiful. The final biodegradable product was pasta, which has become a trending material for environmentally friendly straws (Jonze, 2018). A simple pasta recipe of wheat flour and water was used.

Finally, culinary research was conducted to identify alternatives to common ingredients that would need to be avoided in order to make the product as accessible as possible. This included creating pasta from almond flour opposed to wheat flour to maintain a gluten-free status. Additionally, after seeing promising results from gelatin, a water-soluble protein made from the collagen of various animals, a search for a vegetarian alternative was conducted. Gelatin is a hydrocolloid, meaning that it forms a gel in the presence of water (Phillips, 2009). When boiled, the amino acid chains within gelatin begin to loosen forming a liquid, and once cooled, these bonds reform creating the soft solid structure. Agar-agar, or just “agar” is another hydrocolloid, whose gelling power comes from hydrogen bonds formed in its linear galactan chains when water is added to its dry form, giving it similar properties to gelatin (Phillips, 2009). Agar is both vegetarian and vegan, as it is produced from different varieties of agarophyte seaweeds, commonly called red algae, found mainly in Asian countries (Phillips, 2009).

5.2.1.2 Design Parameter 1 Methods

The experimentation for these seven options was done qualitatively, to observe and understand the properties of the materials and the interactions between different materials. The general objective of the tests was to form a rudimentary cup form and observe its ability to hold water, maintain shape, and not contaminate any contents.

To test the glue recipes, the glues were used to join together pieces of paper towel to test their bonding capabilities. They were then used to coat a piece of paper towel that was in the shape of a cup to understand their ability to hold a desired shape. Paper towel was used as a control material to observe the abilities of the glue. The final test that the glues underwent was an attempt to make an entire cup out of the glue itself. A basic mold was made of two muffin tins to simulate a cup shape, with the glue poured in then pressed into the shape of a cup until dry.

The next set of options were solid materials. The corn husks and the leaves were tested in similar manners. They were cut into different geometries, formed around a mold, and placed in an oven to see if the application of heat would bond the pieces together to form a cup. The different geometries included their natural shapes, thin strips, and fine pieces. Additionally, the corn husks and leaves were coated in the synthesized glues to understand the interaction between the two options. To test the pasta, the wheat flour and water recipe was made. The dough was formed into two cup shapes, and one was left to air dry, and the other was dried in an oven.

After observing the results of the previous experiments, alternatives were explored using almond flour and agar. The almond flour pasta was tested in a similar way to the wheat flour pasta: a dough was made, formed into a cup shape, and left to air dry. The agar was used as an additive to the wheat flour pasta test to see if the hydrocolloid would help bond the pasta more effectively.

Agar was substituted for gelatin in the glue recipe that consisted of gelatin, water, and a bonding agent. Agar was chosen because of its similar gelling properties to gelatin. The substituted recipe was put into a cup mold and allowed to dry, similar to the process used for the gelatin recipe. This agar recipe was observed and qualitatively tested for its ability to avoid leakage and hold shape.

After the creation of each of these samples, qualitative observations were made about their cup potential. They were considered for their ability to form a cup shape, to contain water without leaking, and to avoid contaminating the water held inside. The tests involved applying glue to paper towels, corn husks, and leaves to observe whether or not the glue successfully bonded the materials. After each material was formed into a cup shape and glue was applied, room temperature water was poured into the cup shaped materials and observed the results over an hour period. These qualitative analyses were recorded and provided insight into the next set of tests.

5.2.1.3 Design Parameter 1 Results

The results from these experiments led to an identification of the final non-toxic biodegradable material to act as a base for cup creation as outlined in the first design parameter. A full description of each of the tests and the observations from the experimentation can be found in Appendix A. A complete list of the options examined and the outcome of the testing is detailed in Table 6.

Table 6: Initial Testing Options

Options Tested	Overall Outcome
Corn Husks	Could not be shaped, became brittle with heat
Fallen Leaves	Could not be shaped, became brittle with heat
Pasta	Not gluten free, crack propagation upon drying
Gluten Free Pasta	Contaminated water
Milk-Based Glues	Not vegan, not cohesive
Corn Starch	Reabsorbed water when dried
Corn Starch-Based Glues	Brittle when dried, reabsorbed water
Gelatin-Based Glues	Not vegan, sensitive to cracks
Gelatin	Not vegan, multiple days to dry
Agar-Agar	Vegan, dried well, high melting point

Both of the glue recipes were successful in bonding paper towels. The resulting bond was water resistant, but felt soft to the touch with a gummy consistency. The coated paper towel that was shaped as a cup held its shape well (shown left in Figure 11), but did become slippery when it was wet. The milk-based glue was ruled out because it had a clumpy texture as well as its potential to spoil. The cup that was formed out of just the other glue recipe resulted in a sturdy, water resistant cup that appeared to have potential for further development. This rudimentary cup is shown in Figure 11 on the right.

Figure 11: Glue Coated Paper Towel (Left) and Rudimentary Gelatin Cup (Right)

Both the corn husks and leaves proved challenging to work with when oven dried in a cup shape; no bonding occurred, resulting in the sample degrading. The geometry of the components of the samples did not make a difference. The two materials could be glued together sufficiently, but the issue with the slippery or gummy texture of the glue persisted.

The pasta mixture was formed into a solid cup that was able to successfully hold water. There was no difference in the resulting cup when comparing air dried samples to oven dried samples. However, the water appeared discolored and cloudy when left in the sample for longer than 30 minutes. Additionally, after a few days, the pasta cup developed cracks, indicating a lack of internal bonding. A photo of the broken pasta cup is shown in Figure 12.

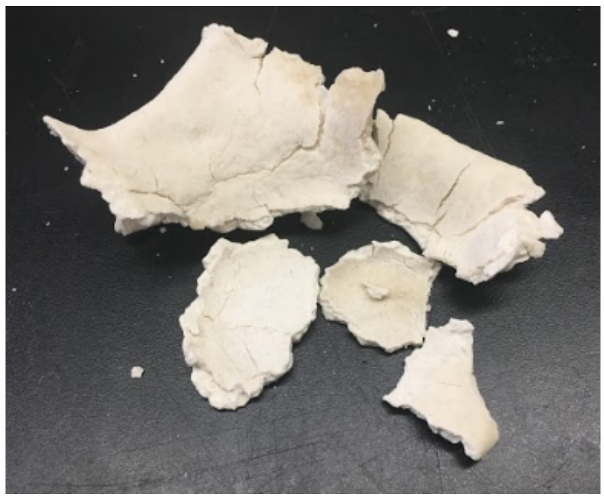


Figure 12: Broken Pasta Cup

Similar to its wheat flour counterpart, the almond flour pasta cup (shown in Figure 13 on left) could be formed into a solid cup, but contaminated water that it held. The attempt to add agar into the pasta to assist with bonding was unsuccessful. The sample was very difficult to create because the agar was boiling when it was added to the dough, and the high temperature prevented kneading by hand. Additionally, the resulting cup still cracked after several days and had a chunky appearance (shown right in Figure 13). Using the gelatin recipe that showed promise, agar was substituted for gelatin. The resulting sample had a similar strength to the gelatin version. It maintained its gelatin like surface for longer than the gelatin recipe, and performed well in a cup shape and did not leak or appear to contaminate water.

Figure 13: Almond Flour Pasta Cup (Left) and Pasta Cup with Agar (Right)

The agar and water recipe was chosen as the base for the material. It held a cup shape, could contain water without leaking, and did not visibly contaminate the water. Other improvements on the gelatin version of the recipe were that it was vegan and had a higher melting point than gelatin. This base met all of the specific parameters of the first DP. It was non-toxic and biodegradable and had a strong potential to lead to the later DPs after optimization and experimentation. A visualization of the outcomes of the first design parameter are shown in Figure 14.

Figure 14: Outcomes from Design Parameter 1

5.2.2 A Structural Material

After the creation of a non-toxic, biodegradable material, the next design parameter is to ensure that this material is structural by remaining sturdy and holding shape. A cup needs to support its weight, as well as the weight of its contents, without collapsing. This design parameter seeks to add more strength to the material to ensure that the final product will function as a cup.

5.2.2.2 Design Parameter 2 Initial Steps

Following the determination that agar would be the base substance of the material, options were explored that could add more structure to the mixture. With the addition of these ingredients, there was concern that the materials would not mix well together. Therefore, another ingredient would have to be added to make the material more cohesive during the manufacturing process.

During boiling of the mixture, there was a visible separation between the agar and water. The ingredients partially mixed together, but were not bonded as completely as desired. To cohesively combine the different ingredients within the material, vegetable glycerin and corn syrup were examined. Both vegetable glycerin and corn syrup are products that have the ability to blend ingredients together that do not usually combine, such as water and oil (Bruso, 2019). It was thought to be useful to ensure the agar, water, and other ingredients added later cohesively combined.

Corn starch is a common thickening agent derived from corn grain (M.J., 2016). The starch thickens liquids upon being heated because its molecular chains unravel and allow it to collide with other starch chains, creating a mesh (Food, n.d.). It was hypothesized that by adding cornstarch, the material would become thicker and more robust. The option in this case would be the determination if cornstarch would or would not be added to the recipe.

In addition to the cornstarch, different hemp fibers were examined to add structure to the cup material. Hemp (a by-product of cannabis production) has a variety of industrial uses, and was one of the first materials that was successfully made into a usable fiber (Hemp, n.d.). It is commonly used to make rope, fabrics, and industrial materials. It can also be used as an insulator and as an additive to building materials. Its strength and durability make it a suitable material for these uses. When discarded, it will completely biodegrade (Hemp, n.d.). It was hypothesized that by adding a variety of hemp, the fibrous structure would enable the material to become significantly stronger.

The two varieties of hemp that were examined were “Natural Hemp Silver” and “Degummed Soft Hemp Fiber.” Natural Hemp Silver, seen left in Figure 15, is used for spinning, and is used to make twine and yarn (Bulk Hemp Warehouse, n.d.). It comes in untwined drawn out fibers and has a dull, dark brown color. It still maintains its lignin, which is a compound that that holds the fibers together, and gives the hemp its strength and rigidity (Bulk hemp warehouse, n.d.). Its fibrous, linear structure was appealing because it could potentially add structure to a cup if it was possible to control the orientation of the hemp within the mixture. Degummed Soft Hemp Fiber, seen in Figure 15 on the right, is much softer and finer than the Natural Hemp Silver. It has had the lignin removed, and is often used as stuffing or for spinning (Bulk hemp warehouse, n.d.). This softer, less fibrous hemp was appealing because it could potentially be used to create a pulp with the agar, which could then be easily molded into a cup shape.

Figure 15: Natural Silver Hemp (Left) and Degummed Soft Hemp Fiber (Right) (Bulk Hemp Warehouse, n.d.)

5.2.2.3 Design Parameter 2 Methods

A qualitative test was conducted to determine if vegetable glycerin and corn syrup successfully increased the integration of the agar and water. Three separate batches of agar were soaked and brought to a boil. One batch had no additives, one batch had corn syrup added prior to boiling, and one batch had vegetable glycerine added prior to boiling. After each batch came to a boil while being stirred constantly, the batches were observed to see how cohesive the mixture would become, and if there were visible pieces of agar that had not combined.

To test whether corn starch successfully improved the structure of the material, standard sized tensile strips were made of the recipe of only agar and water, and the recipe of agar, water, and cornstarch. Qualitative examinations were conducted during the pouring process into the tensile molds. The poured strips prior to drying can be seen in Figure 16. A tensile test was conducted on an Instron 5544. Each test was run by inserting the sample, and having the machine slowly pull apart the strip at a constant rate until the sample broke. The data was collected and graphed for each tensile strip trial.

Figure 16: Agar (Left) Versus Agar and Cornstarch (Right) in Tensile Mold

The two different hemp varieties were then tested for their ability to strengthen the recipe. The two hemp types were cut into pieces and added to the recipe after all other ingredients. Similarly to the cornstarch testing, a batch was made with no additive, a batch was made with the Degummed Soft Hemp Fiber, a batch was made with the Natural Silver Hemp, and a batch was made with a mixture of the two. Qualitative observations were made when pouring the mixtures. The batches were poured into large, thin sheets rather than any mold. This was done to examine how uniform the different material compositions behaved over large areas.

A tensile test was employed to measure the strength added by the hemp fibers. To do this, dog-bone samples were made with and without the hemp. For calculating tensile strength of the material, standard strips were made of the hemp-agar pulp, shown in Figure 17, and then dried. The same method was used on the Instron 5544 to test the hemp-agar strips. Figure 18 shows the strips mounted in the Instron 5544 prior to breaking from the test.

Figure 17: Tensile Strips in Mold with Agar and Hemp

Figure 18: Agar-Hemp Strip Prior to Testing in Instron 5544

For the tests the strip dimensions were measured with calipers and entered into the software for graphing and calculating purposes. The program calculated the rectangular cross sectional area of the strips using the equation *area=width*thickness*. Using the load and displacement graph and values from the tensile test, the tensile strength of the material was determined.

5.2.2.4 Design Parameter 2 Results

After viewing the three batches of agar with no additive, vegetable glycerine, and corn syrup, it was determined that the two additives significantly increased the cohesion of the material. The different ingredients became homogeneous, meaning they were indistinguishable from one another. The corn syrup and vegetable glycerin batches were also indistinguishable, leading to the conclusion that they were interchangeable. It was found that vegetable glycerin was significantly more expensive ($15) than corn syrup ($4), meaning corn syrup was the more economically efficient option. With this in mind, all future samples were made with corn syrup to improve the cohesion and structure of the material.

When examining the samples with cornstarch versus those with no cornstarch, the batch with only agar poured much more smoothly than the batch with cornstarch. However, this made it very difficult to manipulate during pouring, as it acted like a liquid. In comparison to the agar only mixture, the batch with cornstarch was much more viscous, allowing for more control during pouring. This viscosity caused it to maintain shape better, meaning those samples could be removed from the molds more quickly and were more robust samples when handling. The samples with only agar proved to be very delicate, and cracked easily. Crack propagation was prominent in these samples, and upon drying, any crack that was in the sample grew and caused the sample to break apart during drying. The cornstarch samples did not have this issue. There was some crack propagation with these samples, but not as significantly as the only agar samples. The dried out samples with significant crack propagation can be seen in Figure 19. A tensile test was attempted on the samples that had not cracked, however, the samples with only agar shattered from the force of being loaded into the Instron 5544. The cornstarch samples were able to be tested, and those samples are shown in Figure 20. The two samples on the right were not able to be used in the data analysis because they broke due to the force of clamping. Considering the fact that the agar samples were much more delicate than the cornstarch samples, and the cornstarch samples were able to be tested while the agar ones were not, the cornstarch significantly strengthened the mixture. One negative result of the addition of the cornstarch was the creation of bubbles appearing in the mixture when it dried. However, the added strength was considered more valuable than the potential negative effects of the bubbles. It was determined that cornstarch would be added to all samples created moving forward.

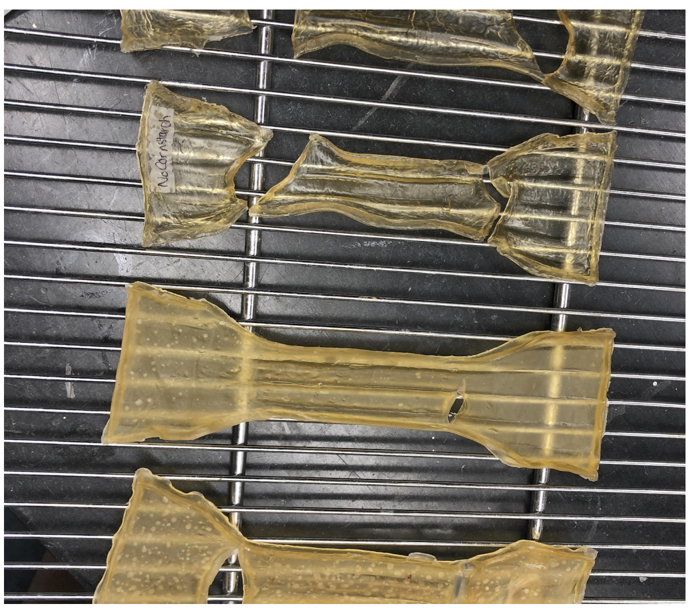


Figure 19: Pre-testing Samples with Cornstarch (Left) and without Cornstarch (Right)

Figure 20: Post-testing Cornstarch Samples

Upon examining the sheets created with the Degummed Soft Hemp Fiber and the Natural Silver Hemp, there were clear differences between how the two reacted with the mixture. The Degummed Soft Hemp Fiber clumped up easily, and it was difficult to evenly distribute it throughout the mixture. This clumping occurred no matter how small the pieces were cut into. In addition, the mixture with the Degummed Soft Hemp Fiber were not aesthetically pleasing. The Natural Silver Hemp also clumped easily when put in long strands, however, it was able to be more evenly distributed when cut into smaller pieces. Despite attempts to try to control the orientation of the hemp, the manufacturing process was complex and would not be viable as a manufacturing process on a large scale. It was found that cutting the hemp into small, 2 centimeters pieces and creating a pulp was the most effective way to incorporate the Natural Silver Hemp into the mixture. The pulp made of Natural Silver Hemp was also the most aesthetically pleasing mixture when dried. Natural Silver Hemp was chosen for all future samples, because the pulp created was the most effective at mixing and looked the best.

The tensile test samples with hemp placed in the Instron 5544 proved much stronger than the mixture with just the cornstarch. The results of the tensile test can be seen in Figure 21.

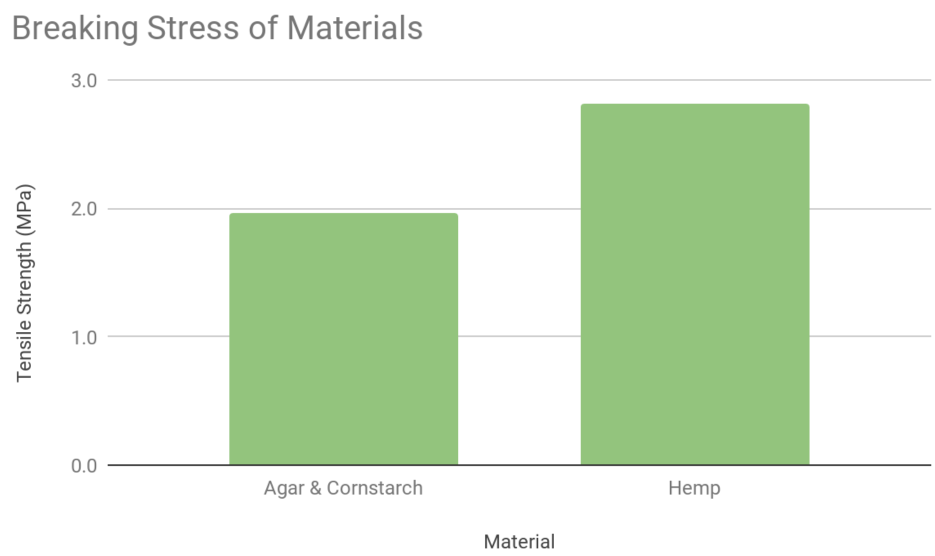


Figure 21: Tensile Test of Samples With and Without Hemp

The added components to the base material increased the strength and structure of the material, successfully fulfilling the second design parameter with the addition of corn syrup, corn starch, and combed hemp pieces. A summary of the outcomes from this design parameter is shown in Figure 22.

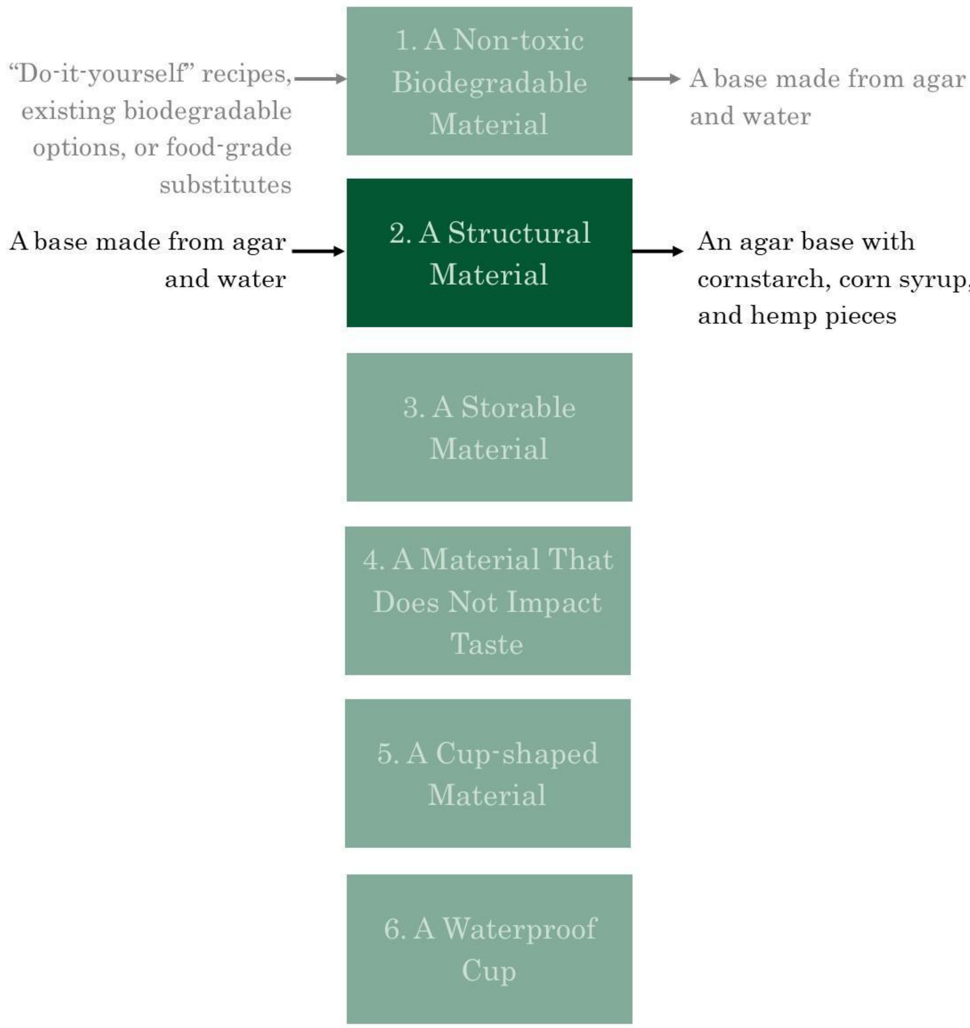


Figure 22: Outcomes from Design Parameter 2

5.2.3 A Storable Material

A structural and biodegradable material was achieved, however it was observed that the samples would shrink significantly when exposed to air, and would grow mold after several days. These observations directly conflicted with the design parameters associated with ensuring the final product could be left in storage. To remedy this, the experimentation of a mold eliminating additive and three methods of moisture removal from the materials are outlined in the following section.

5.2.3.1 Design Parameter 3 Initial Steps

Various options were explored that could add storability to the material through a mold prevention additive and a moisture-eliminating process. The mold prevention additive used to test storage was initially vinegar, due to its ability to break down and remove mold and mildew from surfaces (Thacker, 2010). In addition, drying methods were tested to identify a way to remove the sample's moisture after being formed. Air drying, oven drying, and convection oven drying were explored options. These options were chosen because they were readily available and all had the potential to dehydrate materials as needed.

5.2.3.2 Design Parameter 3 Methods

Samples consisting of an agar base as well as the additives of cornstarch, corn syrup, and vinegar were made using a silicone muffin sheet, where the material was poured into each well as a boiling liquid. Once cooled, the material solidified, allowing these samples to be removed easily and held a convenient puck-like shape. These samples are referred to as "pucks." The puck shape is shown in Figure 23. Hemp was not added in this batch in order to create a blank white puck to easily see any mold that might appear. To test the ability of vinegar as a means for long term storage, six pucks were made with the additive and six pucks were made without. Two teaspoons of vinegar were added to each total batch, meaning each puck contained ⅓ of a teaspoon. These samples were then left to sit in an airtight container. Every day the samples were checked for any mold growth.

Figure 23: Puck Mold and Wet Pucks in Oven for Mold Testing

Nine additional pucks were created out of agar, hemp, cornstarch, and corn syrup, to understand observe the material drying via different drying methods.

To test the efficiency of each drying method: air drying, oven drying, and convection oven, a drying experiment was run for six hours. Three were tested with each drying method. During these six hours, the pucks were weighed at thirty minute increments to observe how much water was leaving the samples over time via the weight percentage decrease. For air drying, the samples were simply left out at a room temperature of 23°C. For both the oven drying and convection oven drying, the samples were put in at 68□ in order to maximize water evaporation without reaching the melting of agar. The data from the three drying tests were compared to determine which would be the most efficient at removing water from the hemp-agar pulp.

5.2.3.3 Design Parameter 3 Results

Comparing the pucks left in an airtight container with and without vinegar, the samples without any vinegar began to show visible signs of mold growth after two days. The samples with vinegar did not grow mold after two days, and remained without mold for the entirety of the research, an observed five months. This test determined that vinegar was a necessary additive to the material to ensure continued storability without mold growth. A comparison between samples with and without vinegar is shown in Figure 24.

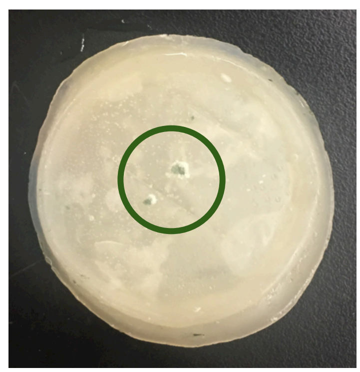


Figure 24: Pucks with Vinegar (Left) and Pucks without Vinegar, Mold Shown in Green Circle (Right)

In the experiment comparing the various drying methods, the air dried sampled had, on average, an eight percent decrease in weight. Oven drying and convection oven drying showed similar results to each other. The samples in the oven reduced sample weight by an average of 60% while convection oven dried samples showed a reduction in weight at an average of 61% as shown in Figure 25. In practice, the process of air drying would be more time consuming and less effective than one of the oven drying methods. The two oven drying methods yielded similar results, but the convection oven's higher percentage of drying made it the best option as well as the ability to leave it unattended since it was industrial grade. The complete set of drying data can be found in Appendix E.

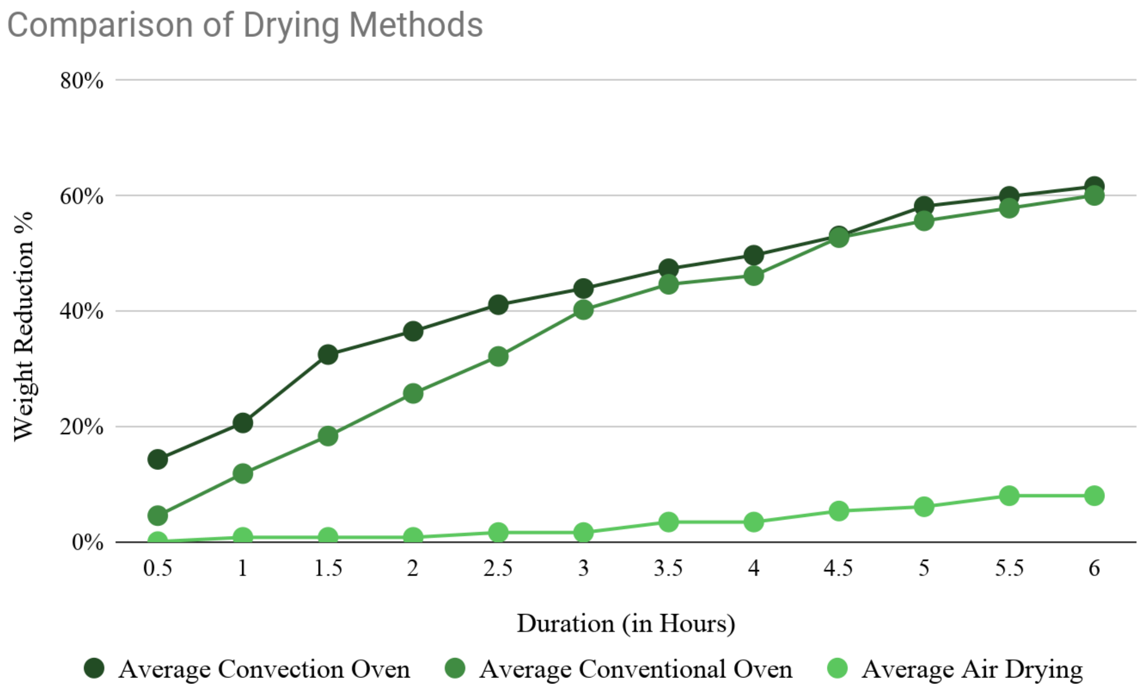


Figure 25: Drying Data

The purpose of the conducted experiments was to ensure the final product could be left in storage for some time without growing mold. Using vinegar, as a mold prevention additive, resulted in samples that did not mold, while those that did not contain vinegar began to grow mold after two days. Consequently, the mold prevention additive was added to the material recipe. In addition, the convection oven drying proved to be the most efficient and consistent method in reducing the amount of moisture left in each cup. Therefore, this was the drying method that was chosen for the final process. These additions to the recipe and production process from the third design parameter are illustrated below in Figure 26.

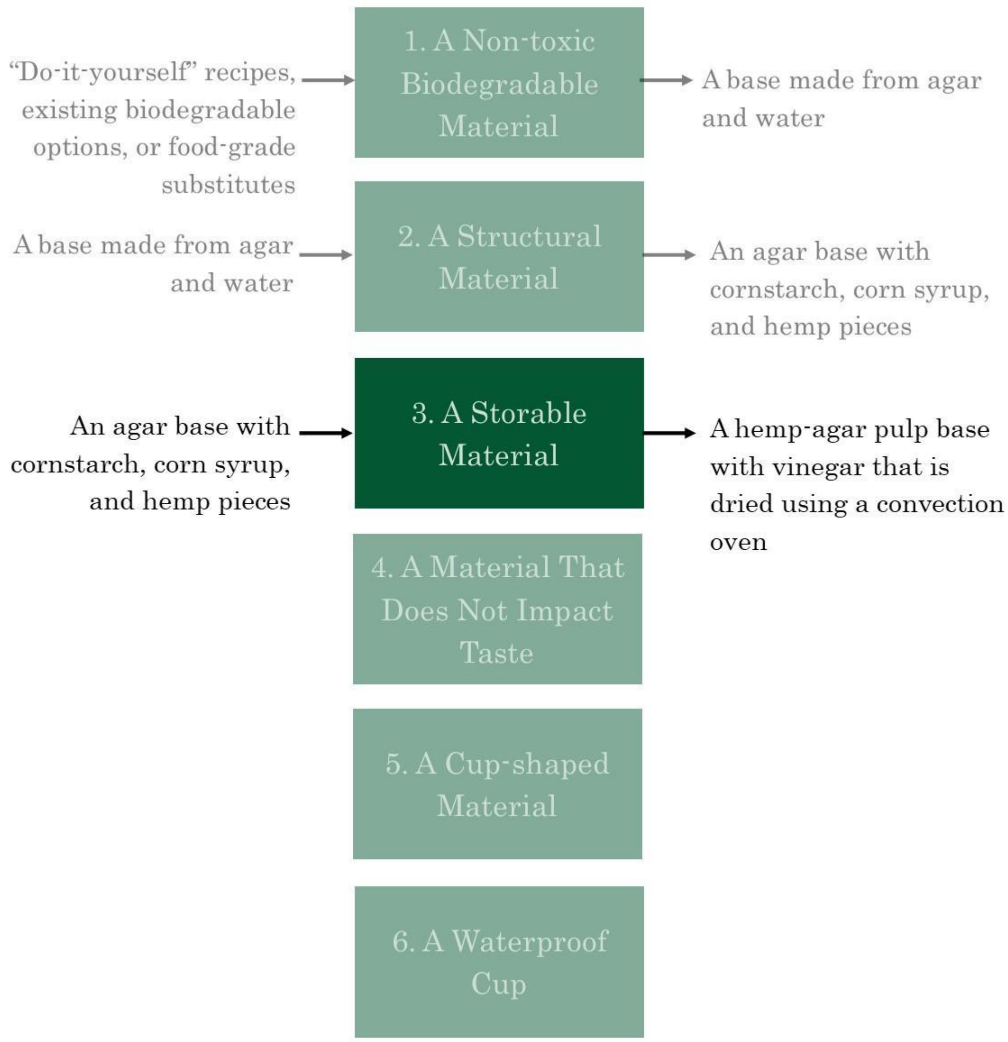


Figure 26: Outcomes from Design Parameter 3

5.2.4 A Material That Does Not Impact Taste

In designing the biodegradable cup, one of the design parameters was to be tasteless and odorless, allowing for the cup to be used without negatively affecting the user experience. An issue that arose after the storability experimentation was that the material had a distinct odor, mainly caused by the vinegar that functioned to prevent mold. The focus of this design parameter was on the odor of the material, due to the restrictions surrounding testing with food grade products.

5.2.4.1 Design Parameter 4 Initial Steps

The hemp-agar pulp was initially created using vinegar to prevent the agar from molding. Despite the samples being left in the oven for water to evaporate, the smell of vinegar was still distinct and unappealing. With such a noticeable smell, it was hypothesized that taste would be affected due to the correlation between scent and taste. Taking into consideration that the vinegar could affect the taste of the cup's contents, other food grade alternatives that would prevent mold from growing on the cup were explored. Viable alternatives to vinegar were determined to be citric acid, lemon juice, and cinnamon, because they all were found to prevent mold growth as well as remain food safe and biodegradable (Cinnamon, 2017) (Levy, 2018).

5.2.4.2 Design Parameter 4 Methods

Pucks were created using the standard recipe without hemp, consisting of agar, corn syrup, and cornstarch, with the variable being the final mold-eliminating ingredient. Hemp was not added to these pucks because the smell could be differentiated most effectively without its addition. The puck samples of these tests are shown in Figure 27. The citric acid, lemon juice, cinnamon, and vinegar were added in 2 teaspoon amounts to the boiling mix. Two pucks of each additive were created for testing. The pucks were then dried in the convection oven so the aroma could be analyzed as it would be when a consumer used the product. A quantitative test was conducted to ensure mold prevention and a qualitative test was conducted to compare the aromas of the dried pucks. The mold prevention test was carried out similar to the test described above in Section 5.2.3, where each sample was left to sit for multiple days and observed each day for mold growth. The aroma test was carried out via a survey where each participant was told to rank the samples from weakest to strongest smelling. The data was then analyzed to see how frequently each mold prevention additive was chosen as the weakest and as the strongest.

Figure 27: Pre-Dried Puck Columns (Left to Right): Lemon Juice, Cinnamon, Citric Acid, and Vinegar

5.2.4.3 Design Parameter 4 Results

The three pucks of each additive type were observed after three days, and all samples successfully prevented mold growth. This meant that the additive was to be selected purely based on the aroma testing. The dried samples used for testing are shown in Figure 28.

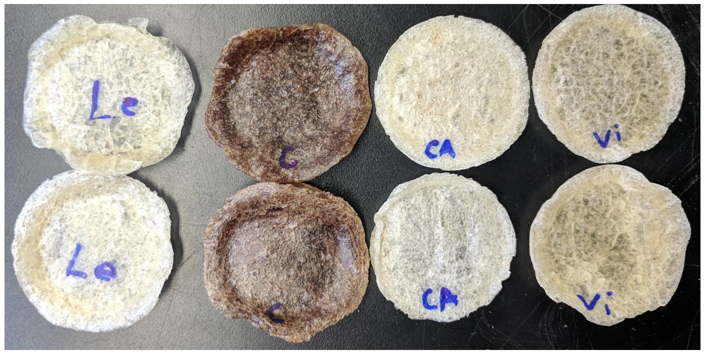


Figure 28: Dried Pucks with No Mold Growth (Left to Right): Lemon Juice, Cinnamon, Citric Acid, and Vinegar

The survey results were relatively consistent across the test subjects. Vinegar was consistently the product with the strongest smell, and those surveyed commented that they believed it would detract from a user experience. Cinnamon also had a strong scent, and was consistently ranked the second strongest smelling. Citric acid and lemon juice had a significantly weaker scent, which was almost undetectable in the puck. When it was detected, the citric acid had a sour smell while the lemon juice had a neutral smell. Frequency charts of the weakest smelling material (Figure 29) and strongest smelling (Figure 30) are shown below.

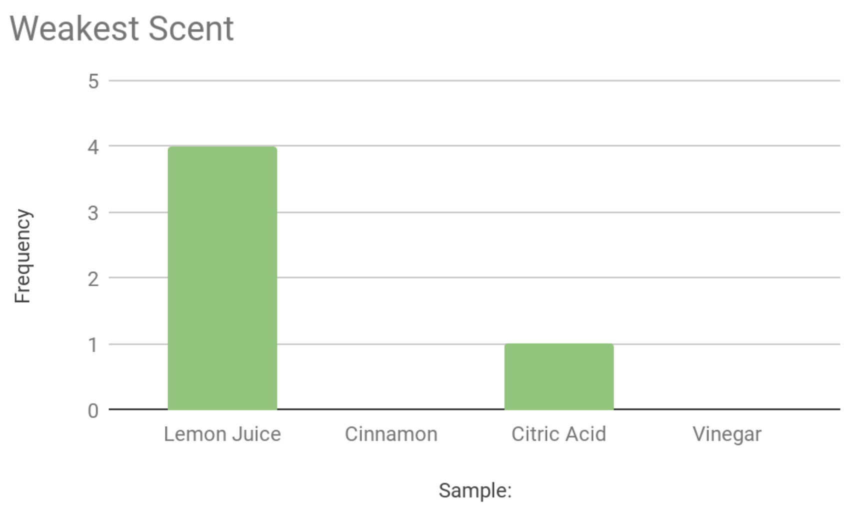


Figure 29: Frequency of Weakest Smelling Mold Prevention Additive

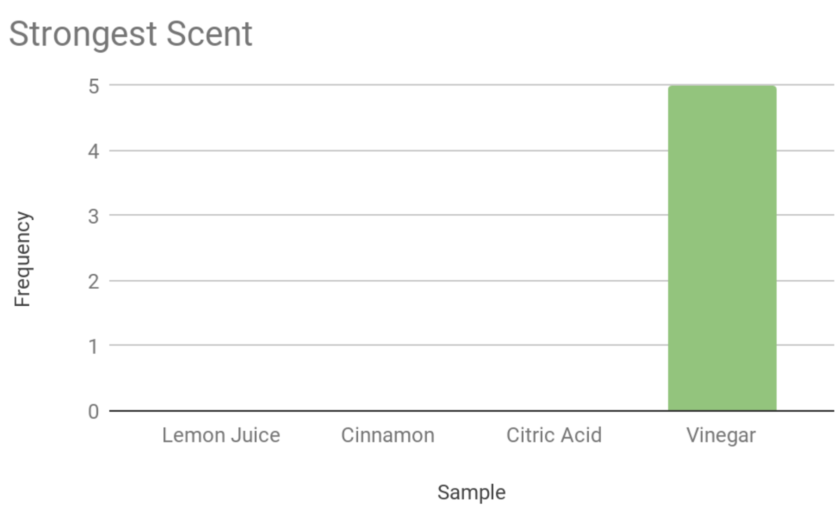


Figure 30: Frequency Strongest Smelling Mold Prevention Additive

Lemon juice was chosen for the final material because it was distinctly the least noticeable smelling additive as it was chosen first four out of the five tests, and was never chosen as last. The outcomes from this parameter are visualized in Figure 31.

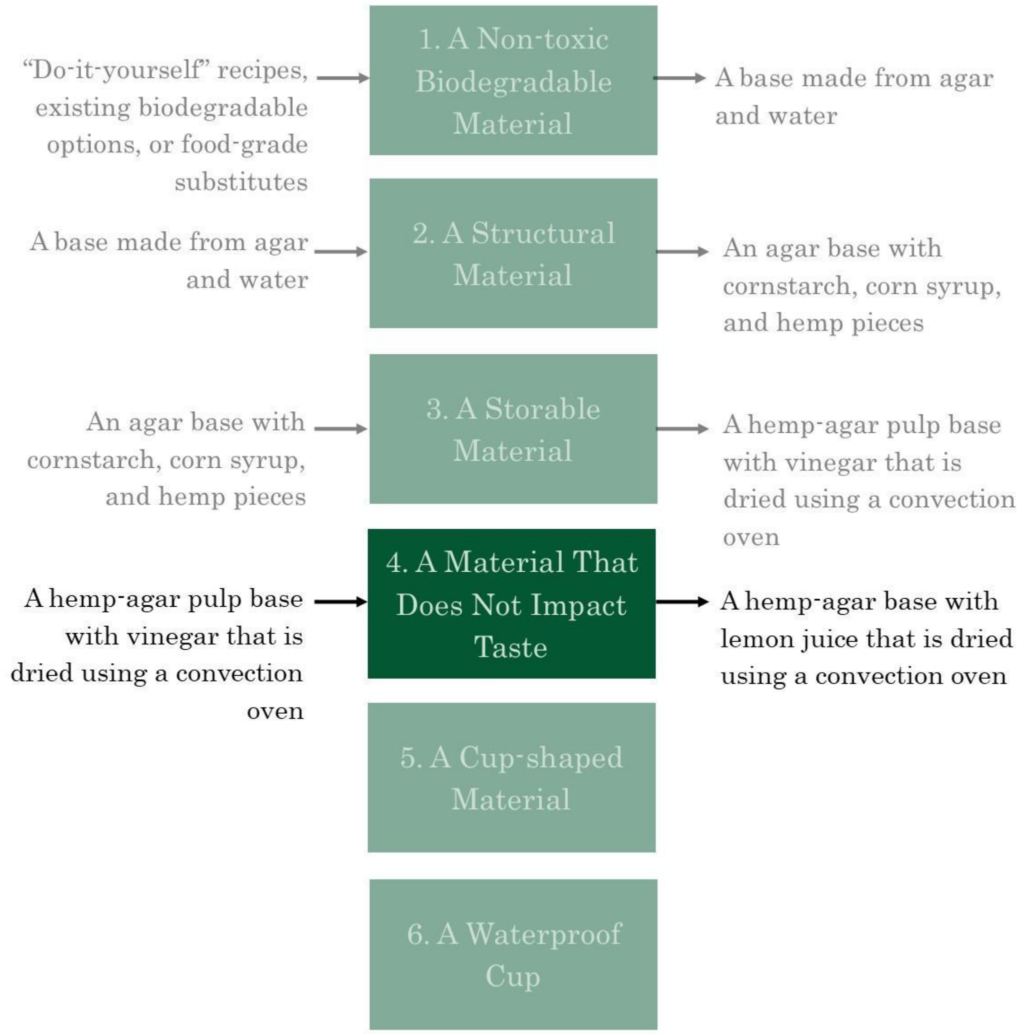


Figure 31: Outcomes from Design Parameter 4

5.2.5 A Cup-shaped Material

Once the final material was established (a non-toxic, biodegradable, structural, storable, and odorless material) the next step was to form it into a cup shape. This design parameter was made to fulfill DP 2.0 in full. The general objective was to make a cup, and this parameter is focused on developing that shape and improving the process by which it is done.

5.2.5.1 Design Parameter 5 Initial Steps

To ensure the material was a viable option for forming a cup, the material must be able to hold its own form without assistance. If a material was unable to hold its own shape, then it was ruled out as a possibility. The majority of cups on the market followed either a cylindrical or draft angle geometry. Using this popular cup geometry the options of a 3D printed draft angle mold and a silicone mold were explored. Initial designs were small cups of approximately two ounce volume capacity. Experimentation with hemp-agar tensile strip samples, showed after removal from tensile mold and placing them unsupported into a convection oven to dry, the samples would curl and wrinkle. It was important to address this issue as it could possibly affect the cup's ability to maintain shape during drying. This concern was confirmed to be a problem with the first iterations of large-scale cup drying. To prevent the hemp-agar pulp from constricting during the drying process a structural support to resist the force of the cup curling during drying was needed, while still maintaining optimal airflow for even drying. The following options explored were to use a metal wire mesh or high temperature 3D printed air drying mold. The first option, the metal wire mesh, would allow for optimal airflow during the drying process and was easily formed by hand. The second option, 3D printed mold used a high temperature PLA to support the cup uniformly and provide optimal airflow throughout its drying process. A model of the high temperature PLA mold is shown in Figure 32.

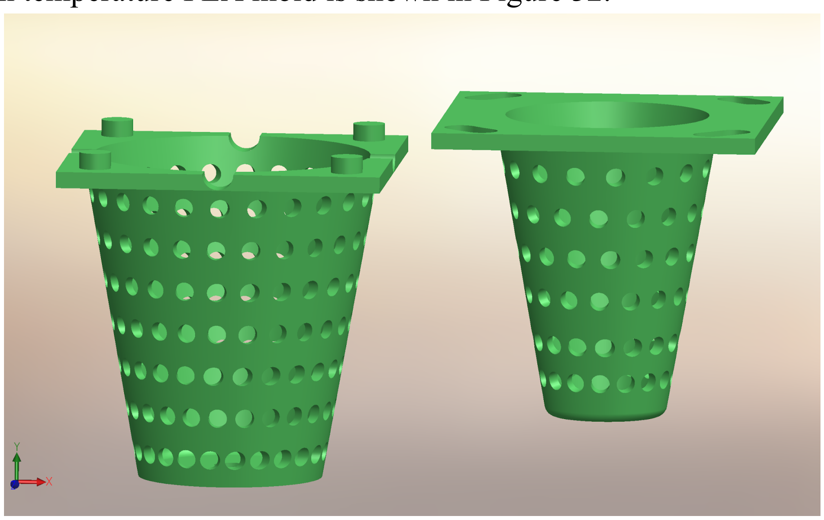


Figure 32: CAD Model of PLA Drying Mold

5.2.5.2 Design Parameter 5 Methods

In order to achieve two different cup geometries, different type molds were tested. A stiff 3D printed PLA mold was used to form cups with a draft angle, while a flexible silicone mold was used for cylindrical cups. These mold are shown in Figure 33 and 34, respectively.

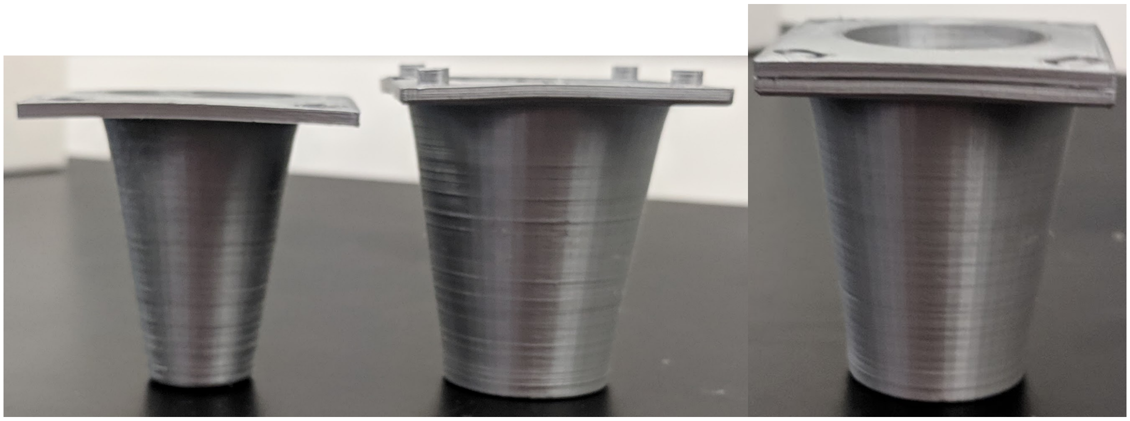


Figure 33: PLA Mold for Cups with Draft Angle

Figure 34: Silicone Mold for Cylindrical Cups

The 3D printed mold incorporating a draft angle was made up of an inside and outside cup shape that locked together via pegs at the top to center the inside piece and ensure even wall thickness. The mold was originally created as a portion cup that held approximately two ounces of liquid. This mold allowed for the hemp-agar pulp to be poured into the outside component of the cup, then pressed using the inside component of the cup so the material would rise up the sides of the mold into the available space. The hemp-agar pump cooled and solidified in this form, and was then removed by twisting the two pieces in opposite directions to break free of the edges.

The silicon mold, was used to create a cylindrical cup with no draft angle. This mold was also created as a portion cup that held approximately two ounces of liquid. This mold allowed for the hemp-agar pulp to be poured in from the top. Once filled, the sample solidified in this form, and was removed by carefully pushing the silicone mold inside out and removing the cup from the inside.

After the cups were formed, they received either the wire mesh support or 3D printed support. These supports were mainly created to help guide the cup to the desired final shape by keeping it in desired form. In order to allow proper drying they also allowed for ventilation to make sure the cup could dry out thoroughly. The wire mesh support was shaped by hand for the interior and exterior of the cup and inserted prior to going into the oven for 24 hours. The 3D printed drying support used interior and exterior supports which were printed using the same dimensions from the cup mold, but with new ventilation holes added, and placed on the undried cup prior to going into the oven for 24 hours.

5.2.5.3 Design Parameter 5 Results

During the forming process, the hemp-agar pulp was easily molded and released from both cup mold geometries while maintaining their shape. The cylindrical cups from the silicon mold dried in an hourglass shape as shown in Figure 35. The cups from the 3D draft angle showed more promise after initial drying. During the drying process, the metal wire mesh gave the desired effect to the inside, drying more smoothly and evenly than without. Although, using this method provided inconsistent results as it required both the interior and exterior metal wire mesh to be formed by hand. The final appearance of the cups after drying in the industrial convection oven can be seen in Figure 36. The cups which dried on the 3D printed drying support gave similar results to the wire mesh, although this drying method could not be pursued any longer because the inside piece broke upon removal. The 3D printed support's rigidity gave support during drying but made it impossible to remove from the dried cup without damage to the cup or mold. This was not seen as a cost effective way in comparison to the reusable mesh supports. Therefore, the metal wire mesh was selected moving forward to provide support to the cup during the drying process. Through this experimentation method, not only was it proven that the material was able to maintain shape, but a method for improved shape was found.

Figure 35: Silicone Mold Dried Cups

Figure 36: Dried Cups from Draft Angle PLA Mold and Wire Mesh Support

Initially the cup held shape once solidified but dried unevenly and looked warped after moisture removal in the industrial convection oven. This testing aimed to have the cup dry while still maintaining its functional cup shape and its aesthetically pleasing appearance. Figure 37 shows that from this testing, the process revealed the draft slope angle mold with the inner mesh supports was best for achieving the desired cup shape.

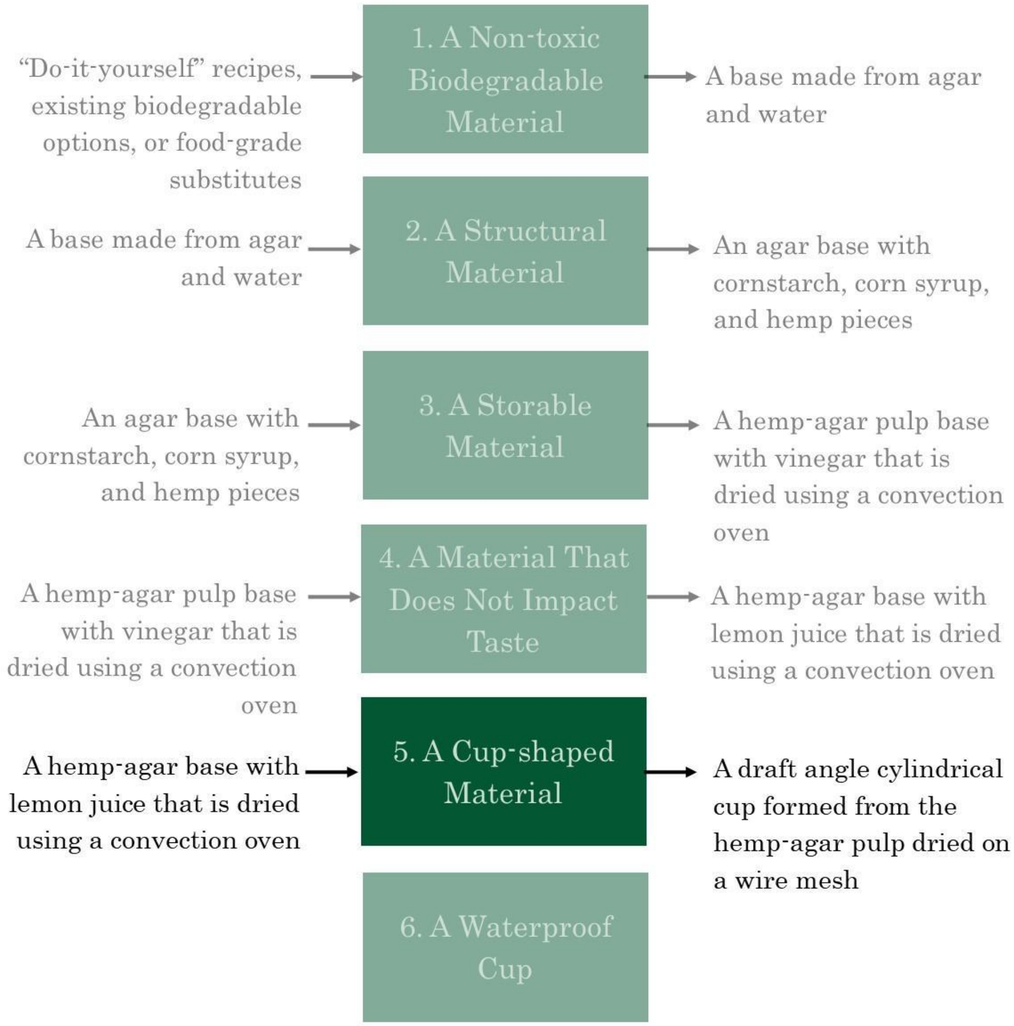


Figure 37: Outcomes from Design Parameter

5.2.6 A Waterproof Cup

DP 2.0 included a sub-parameter with the goal to ensure a watertight container. The hemp-agar pulp did not fulfill this on its own due to the material absorbing water. Additional treatment was required to meet this requirement. Thus, an application of a waterproof film was necessary for the interior of the cup making the cup completely watertight.

5.3.6.1 Design Parameter 6 Initial Steps

Ensuring the cup does not absorb any of the internally held liquid is critical to its usability. The agar-hemp pulp was tested on its own measuring its ability to be hydrophobic without a waterproof film treatment. Various wax coatings were tested on the material to create a hydrophobic coating over the material. Beeswax, carnauba wax, C-3 Nature Wax, candelilla wax, and a wax used to treat bamboo were examined.

5.2.6.2 Design Parameter 6 Methods

To test the capability of the hemp-agar pulp serving as a cup, several water temperature-based tests were carried out. These tests all used fully dried out pucks of the hemp-agar pulp, as this is the condition they would be in when a user was pouring liquid into them. The pucks were all weighed at the start of the test to have an initial measurement for comparison. The pucks were labelled to allow for weight tracking. The pucks were then left submerged in water of varying temperatures: hot, cold, and room temperature. The hot and cold water was poured in at the extreme temperatures, at the start of the experiment, gradually cooling or warming up until reaching room temperature. The test was determined to be over when the hot and cold water returned to room temperature, and at that time the pucks were weighed again.

Hot water testing was done using water at 84□, a common serving temperature for hot beverages. A small glass dish was filled with the hot water and the pucks were then placed in the dish, fully submerged. The pucks were left submerged in the water until it returned to room temperature, which took approximately 4 hours. The pucks were then weighed again to determine the amount of water absorbed, as well as handled to check for stiffness, appearance, and overall ability to maintain form. An additional test was conducted with hot water where the pucks were only half submerged in shallow water. This test better modeled the interaction of water and a cup as only one side of the material is in contact with the water. This test also ended when the water returned to room temperature. Figure 38 shows the half-submerged pucks at the end of the experiment.

Figure 38: Half-submerged Pucks in Hot Water at End of Testing

Cold water testing was done by adding ice to water in a glass dish. The pucks were added after the water temperature dropped and stabilized at 3 °C. Similar to the hot water test, some samples were left fully submerged and others were partially submerged in the water dish until the water returned to room temperature. Pucks in the cold water were tested after 2 hours and 45 minutes of soaking.

Room temperature (19 °C) was done in the same general manner as the hot and cold test but instead of waiting for the temperature to change, pucks were observed for over 24 hours. Figure 39 shows several samples after they had been fully submerged for 24 hours. More test samples were used in room temperature testing than hot or cold because the cups are most likely to interact with room temperature liquids more than anything else. This test was conducted for 24 hours to simulate scenarios where a drink would be left in a cup for a long period of time, such as overnight or on a desk all day.

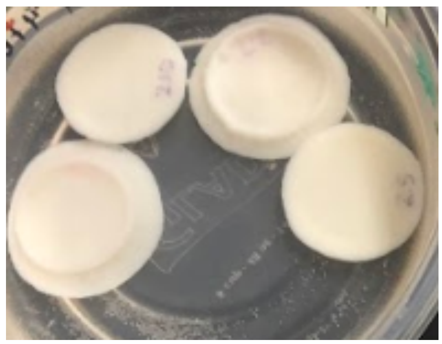


Figure 39: Fully Submerged Pucks at End of Testing

Various waxes were tested to determine their waterproofing capabilities. Additionally, each wax was applied in thin layers to determine the least number of coats required to prevent the cup from absorbing water. The five waxes tested were: carnauba wax, beeswax, C3 NatureWax, candelilla wax, and a bamboo treatment wax. All these waxes have varying material properties affecting cohesion and melting point. Table 7 below for the differences between these waxes.

Table 7: Varieties of Tested Waxes

Type of Wax	Melting Point (°C)	Vegan (Y/N)	Common Uses
Beeswax	62-64	N	Candles, cosmetics
Carnauba Wax	82-86	Y	Automobile wax, food additive
C-3 Nature Wax	50-54	Y	Candles, wax coatings
Candelilla Wax	68-72	Y	Food additive, cosmetics
Bamboo Wax	20-25	Y	Coating bamboo products

The waxes were bought in solid pieces and melted using a double boiler over a hot plate. A paint brush was used to coat the inside of the cups with an even coating of the wax. Multiple layers were tested to determine the point where the wax was creating a completely waterproof seal on the cup's material. Each wax was applied to several cups. Bottled Dasani water was used as the testing medium. The cups were tested with water for 24 hours in order to simulate the amount of time required for a normal cup to hold water. Three tests were then conducted on each sample to determine the turbidity, pH level, and electrical conductivity of the water after 24 hours. Dasani water from the bottle was measured as a control, as well as a cup that was not coated with any wax, to see the difference between the coated and non-coated cups.

Turbidity tests measure the scattering of light within a sample of water. The more undissolved particles contained in a water sample, the greater the turbidity. Turbidity is measured in Nephelometric Turbidity Units (NTU). A sample image comparing the turbidity of five samples can be seen in Figure 40. The purified water was held within two samples of each of the five wax coated cups and two of the uncoated cups. After the 24 hour period, each of the water samples were then placed in the 2100N Turbidimeter to measure the turbidity of the water. Once the turbidity of samples was determined, the respective NTU values were compared. The World Health Organization specifies that drinking water must at all times be under 1 NTU, meaning the chosen cup must be below this value (WHO, 2017).

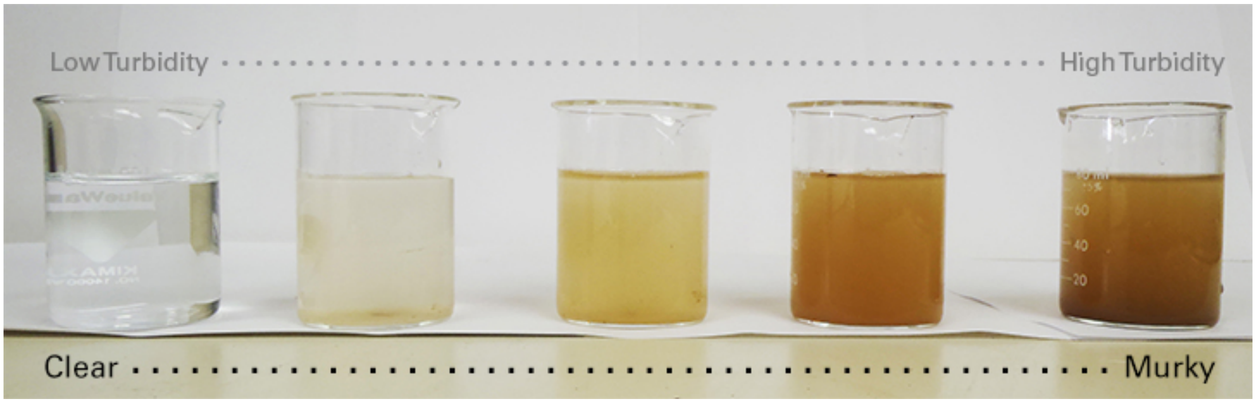
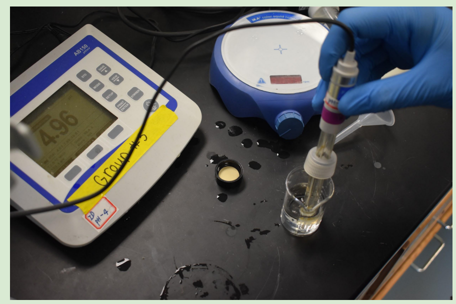


Figure 40: Turbidity Scale (PacIOOS)

pH testing provided information about the cups impact on the water's acidity. Purified water samples were kept in the hemp-agar cup covered in the various waxes outlined above. A pH probe was used to measure the pH of each of the contained water samples. The EPA notes that the pH of drinking water should be between 6.5 and 8.5 to eliminate any amount of acidic taste (US EPA, 2015). That being said, it is noted that pH is an aesthetic value related to drinking water and can range widely on the pH scale.

Lastly, electrical conductivity testing determined the concentration of dissolved ions in the water due to the various samples The conductivity tester was then placed within the water samples and the results were recorded. The resulting values were used to determine the content of dissolved particles. Like in the two tests above health organizations such as the EPA have specified that drinking water must be below 2500 micro s (EPA, 2014). In order for the cup to meet these drinking standards, it cannot affect liquids beyond this point. A summary of the water quality testing method is shown in Table 8.

Table 8: Explanation of Water Testing Methods

Water Testing Methods	**Purpose**	**Equipment Used**
Turbidity	Measure the scattering of light within a sample of water	
pH	Measure water's acidity.	
Conductivity	Measure the concentration of electrolytes dissolved in the water	

5.2.6.3 Design Parameter 6 Results

Figure 41 shows the weight of the pucks before and after being submerged in the hot, cold, and room temperature water, and Figure 42 shows the weight of the pucks that were half submerged. The hot and room temperature water testing showed a significant increase in weight after 24 hours, indicating that they had reabsorbed some of the water. The cold water pucks lost weight, this is believed to be a testing error, as parts of the puck flaked off when rehydrated. All of the pucks tested had a change to their physical appearance and texture. They gradually returned to their pre-dried opaque white color further indicating that they were absorbing the water. Despite this, all pucks tested maintained their ability to hold shape and were rigid. The partially submerged pucks remained dry at the top and were more rigid than the fully submerged pucks, meaning that only the parts of the puck that touched water rehydrated. The hot water pucks did begin to deteriorate at the edges, with some particles breaking off into the water, giving the edges a slightly ragged appearance. The cold water tested pucks had the smallest visible change in characteristics, with slight fraying on the edges, similar to the hot water testing. Excluding the pucks in the cold water testing, the remaining pucks all gained weight from absorbing the water and grew in size as they rehydrated. This experiment emphasized the need for a hydrophobic coating on the cups to make them usable.

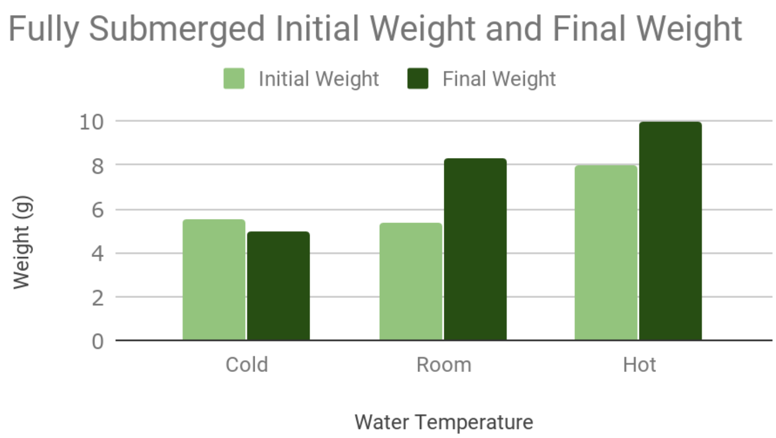


Figure 41: Fully Submerged Puck Water Testing

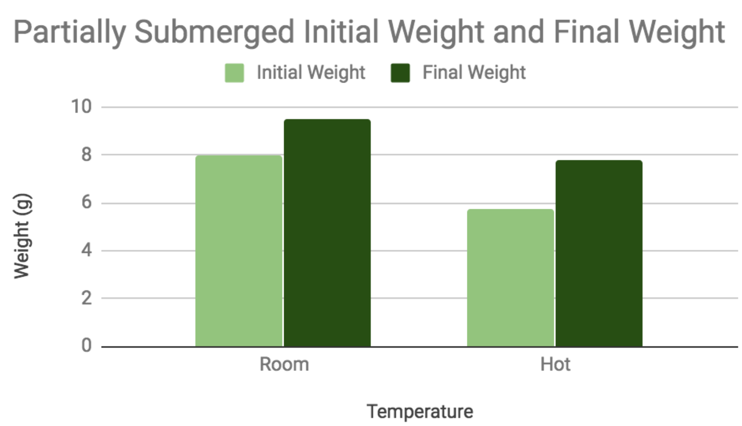


Figure 42: Half Submerged Puck Water Testing

The turbidity, pH, and conductivity tests produced significant results that showed the best option for a wax coating and number of layers used. From the water quality tests it was found that candelilla wax, at three coats was the most effective at waterproofing, as well as not affecting the turbidity, pH, or conductivity of the water. Candelilla wax was the only wax tested with both two and three coats because qualitative observations of the cups after coating with the material showed that it was the only option that did not become too thick or begin to flake when three coats were applied.

In the turbidity testing, the candelilla wax cups had the least turbid water. All other samples were more turbid than the uncoated cup filled with water. This is likely due to wax cracking and flaking into the water, increasing particulate matter. Nature Wax had the highest turbidity with many visible flakes after 24 hours, as well as giving the water a yellow color. This can be seen in Figure 43 below. Uncoated samples showed to have a lower turbidity than coated samples meaning that not much of the material breaks away into the water, however the uncoated samples absorbed the water. This observation means the material is water resistant, but not waterproof. The results of this test can be seen in Figure 44, and a complete data set can be found in Appendix D.

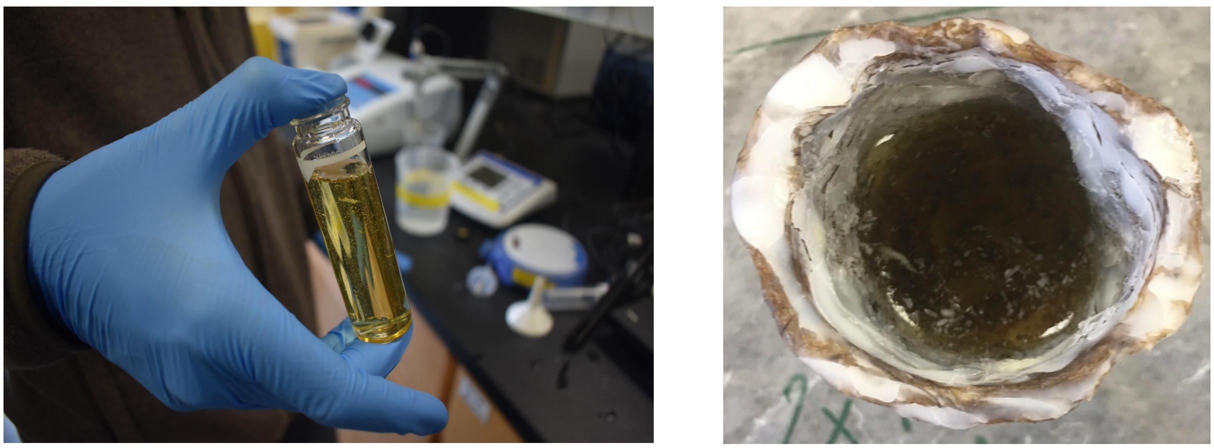


Figure 43: Nature Wax Water Test Sample (Left) and Nature Wax Cup Interior (Right)

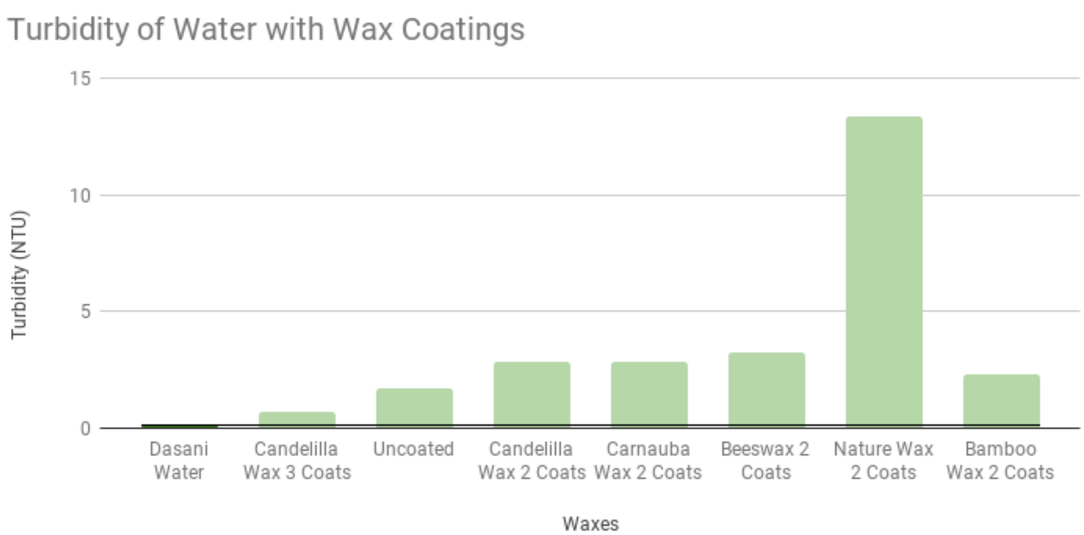


Figure 44: Turbidity of Water with Wax Coatings

The conductivity of the water was least affected by the cup with the triple layer candelilla wax coating. The uncoated cup was again less affected than any of the other wax coatings. For all the other waxes, the water was significantly more conductive. There was a slight increase even with the three coated candelilla wax, however it is nowhere close to any of the other waxes or the EPA standards for conductivity. This shows the significance of the wax coating, and that it was able to successfully prevent the material and water from coming into contact. The results of this test can be seen in Figure 45.

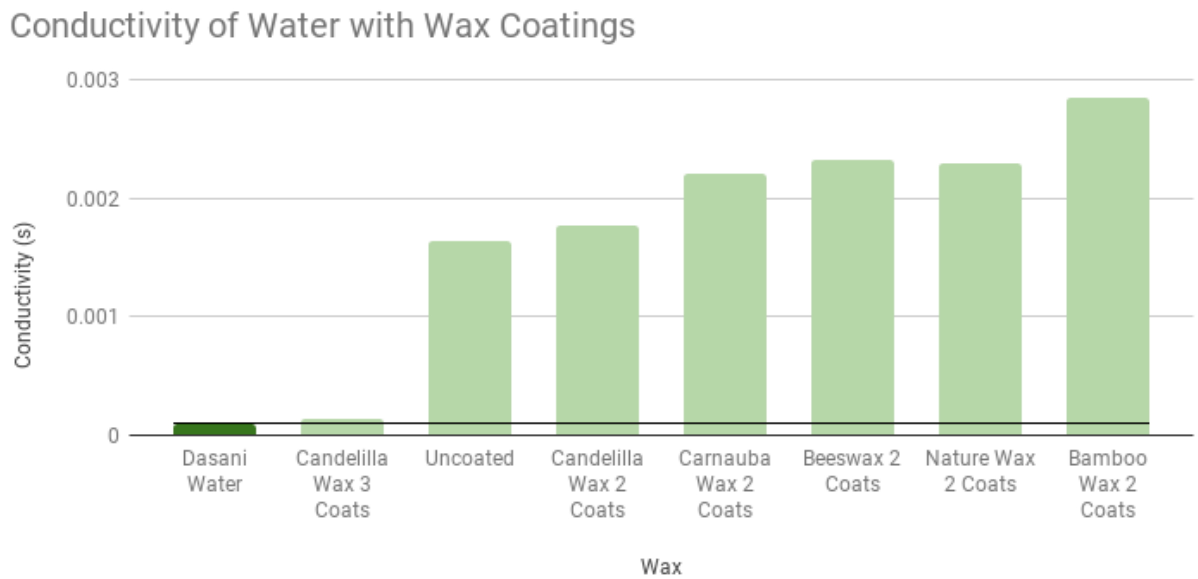


Figure 45: Conductivity of Water with Wax Coatings

Finally, the pH of the water was also the least affected by the three coats of the candelilla wax. The uncoated cup and all other wax coatings made the water slightly more acidic, but there was not much difference between the other waxes and uncoated sample. This data can be seen in Figure 46.

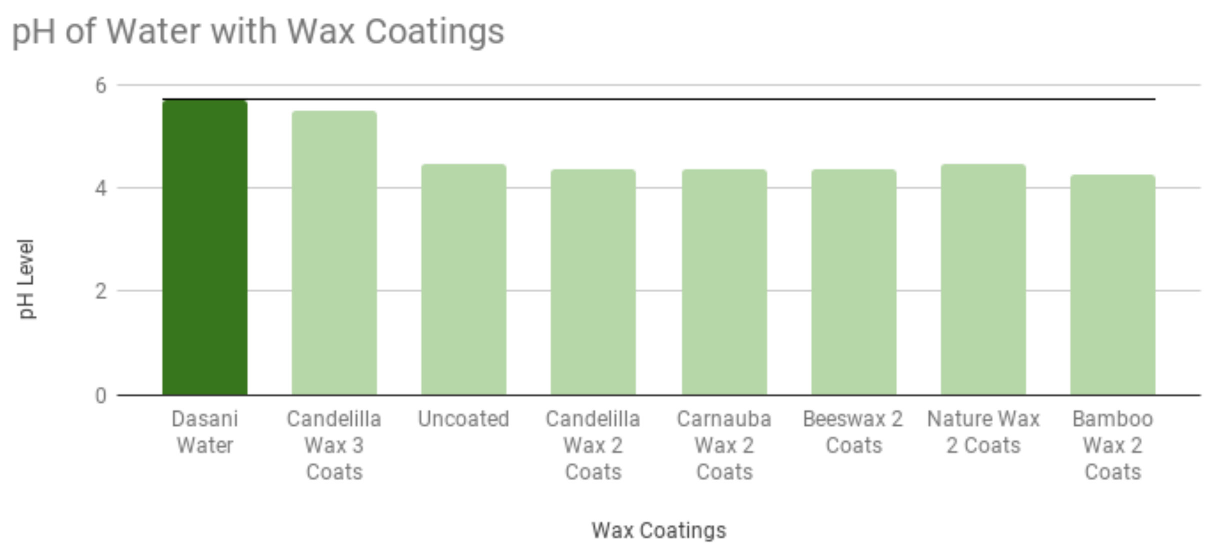


Figure 46: pH of Water with Wax Coatings

Three coats of candelilla wax was chosen as the hydrophobic coating for the cups, because of the results of the three water quality tests. The outcomes from the sixth design parameter are illustrated in Figure 47 below.

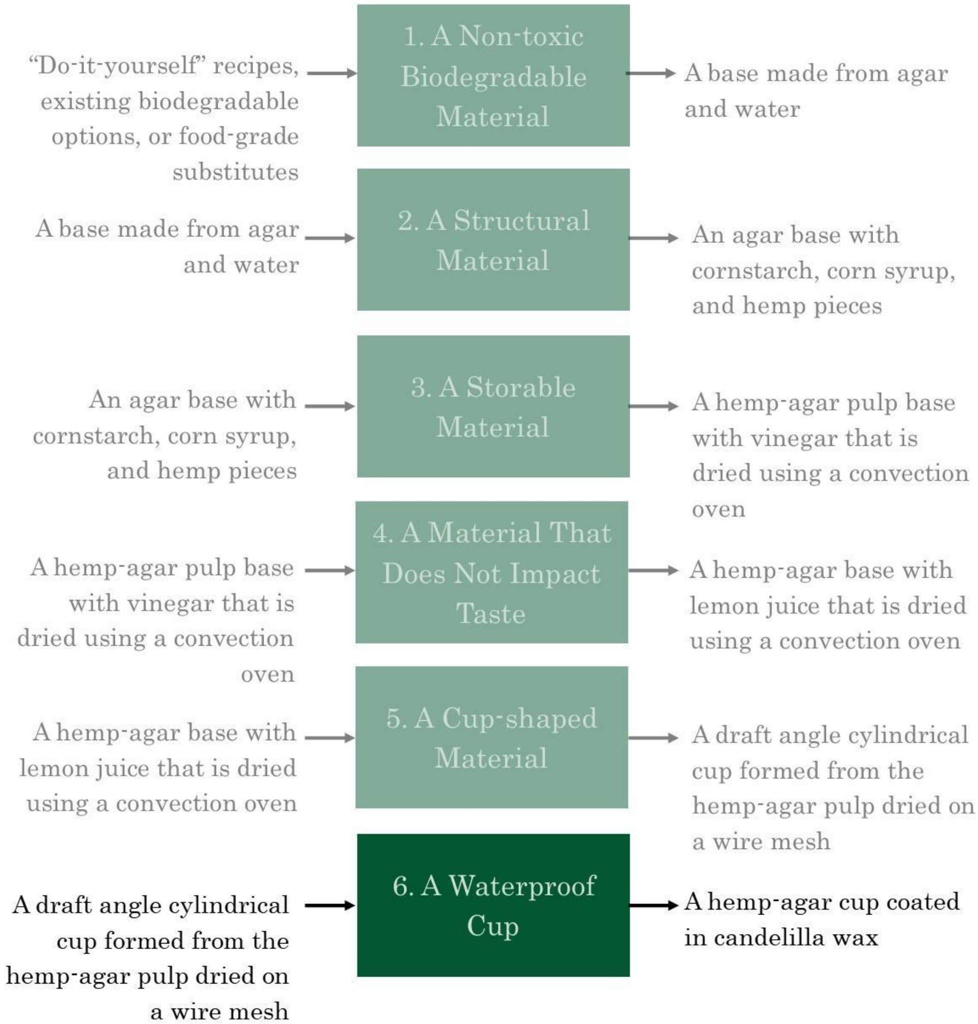


Figure 47: Outcomes from Design Parameter 6

5.3 Final Design Procedure

The design parameters defined in Section 5.1 allowed for a logical design process to be followed. Parameters were fulfilled one by one in an order that prevented previous design choices from being undone. After concluding the design process, the procedure for the production of the cup was to complete the following steps:

1. Mix boiling water, agar, corn syrup, corn starch, and lemon juice until smooth
2. Add in finely chopped hemp pieces
3. Pour hemp-agar pulp into the cup mold
4. Allow hemp-agar pulp to harden in mold
5. Remove hardened hemp-agar pulp from mold and place in oven at 67 degrees Celsius
6. After 12 hours remove cup from oven
7. Coat interior of cup with layer of candelilla wax

The production process is briefly shown in Figure 48. A detailed production procedure can be found in Appendix B.

Figure 48: Overview of Production Process

6.0 Material Analysis

Water and strength testing of the material was done to compare the cup developed in Chapter 5 to non-biodegradable competitors on the market such as plastic, styrofoam, and paper. The results of these tests are able to confirm that the material created is comparable to the cups that are currently on the market. In order for the cup to be a realistically viable substitute, it has to be on par with is currently used by consumers.

6.1 Water Quality Testing

Water quality testing was conducted to observe the effect of the cup on the water contained using quantitative tests. For these tests the water was tested after interacting with the cup, but the cup itself was not specifically observed. The three tests, described in Figure 49 and the same tests conducted in chapter 5, were used to observe the effect on the contained water: turbidity testing, pH testing, and conductivity testing.

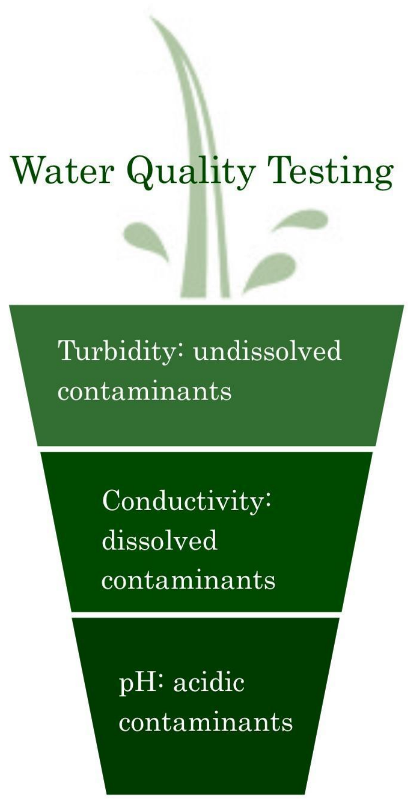


Figure 49: Water Quality Testing Overview

6.1.2 Water Quality Methods

Dasani bottled purified water was held within the candelilla coated and uncoated hemp-agar cups as well as a plastic, styrofoam, and different paper cups uncovered for 24 hours. Photos of the wax-coated hemp-agar cups after 24 hours of holding water are shown in Figure 50. There were two cup samples for each cup type which were then mixed together in lab glassware for an averaged results. The cleaned glassware was used because did not affect what it contained. Some purified water was left in the original bottle to be used as the unaltered control sample. This method was conducted once for all of the water tests detailed under Section 6.1.

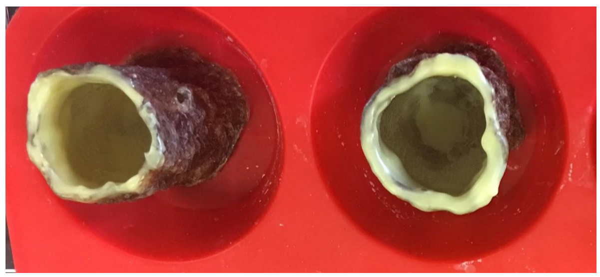


Figure 50: Candelilla Wax Coated Cups Filled with Water for 24 Hours

Turbidity tests measure the scattering of light within a sample of water. The more undissolved particles contained in a water sample, the more turbid it is. After the 24 hour period, each of the water samples was placed in a glass vial and then into the 2100N Turbidimeter to measure the turbidity of the water. The glass vial acted as a transparent container through which light shined through. The 2100N Turbidimeter is calibrated yearly, and was up to date for these tests. Turbidity is measured in Nephelometric Turbidity Units (NTU). Once the turbidity of samples was determined, the respective NTU values were compared.

pH testing provided information about the cups impact on the water's acidity. Samples of the hemp-agar cup, plastic, styrofoam, and two different paper cups contained purified water for 24 hours. After calibrating with 3 varying known pH samples, a pH probe was used to measure the unknown pH of each of the contained water samples.

Lastly, conductivity testing determined how many dissolved particles existed in the water. The conductivity tester was placed in the water sample until the reading stabilized and the result was recorded. The conductivity measuring equipment, similarly to the Turbidimeter, is calibrated yearly and was up to date. The resulting values from testing were used to determine the content of dissolved particles.

6.1.2 Water Quality Results

The control sample for the water experiments was Dasani water packaged in a plastic bottle which had a turbidity reading of 0.092 NTU. This sample was used as the baseline for comparison. The current market options for cups (styrofoam, plastic, paper, and biodegradable paper) had the lowest change in turbidity. Biodegradable paper had a reading even lower than the control sample at 0.083 NTU. The water sample from the candelilla coated hemp-agar cup had a turbidity of 0.66 NTU. The cup visibly produced the most turbid water. This was expected, since the candelilla coated hemp-agar cup is not yet perfected, while the cups currently on the market are mass produced and have been optimized over the years. More optimization of the cup is necessary, but it still produces a change in turbidity that is acceptable by EPA and WHO standards (EPA, 2015) (WHO, 2014). A chart comparing the turbidity of the different cups is shown in Figure 51.

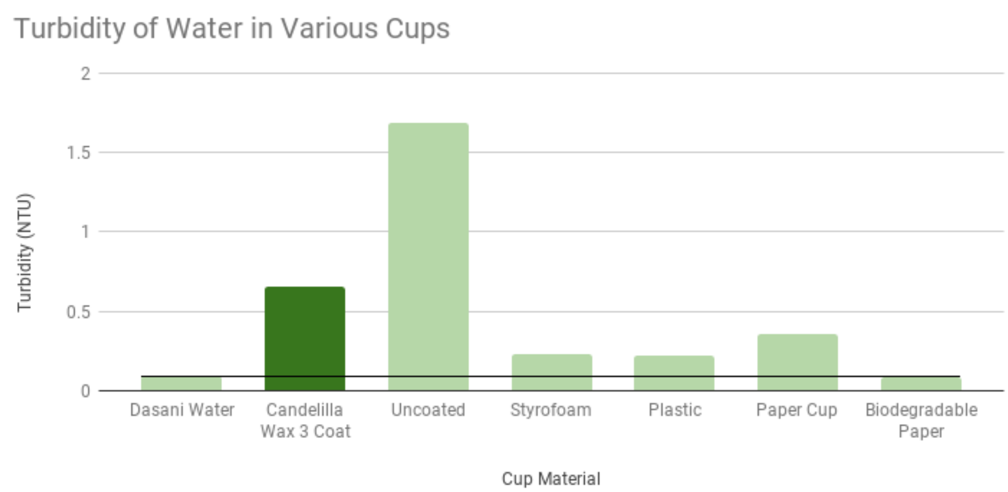


Figure 51: Chart of Samples' Turbidity

Dasani bottled purified water had a low pH by EPA standards at 5.7. The measured pH levels of samples are shown in Figure 52.The common market samples of styrofoam, plastic, paper, and biodegradable paper had low changes in pH. They all had a small rise in pH less than 1. The cup only lowered the pH by 0.19. This is promising, because the cup affected the water less than the products already on the market.

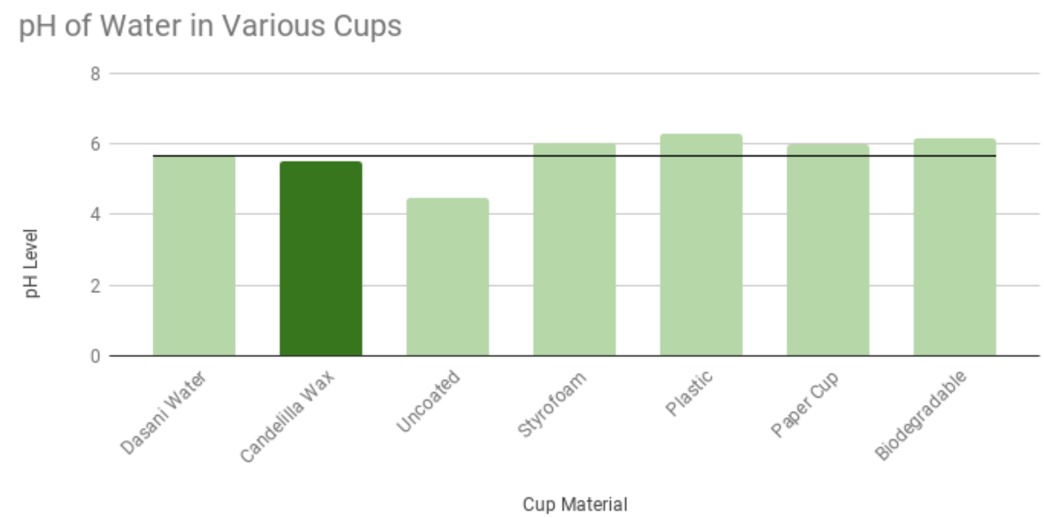


Figure 52: Chart of Samples' pH

The market samples showed the least change in conductivity from the control sample, however, the candelilla wax with three coats was less than 0.0001 s higher than the competition. The uncoated cup was significantly higher than any other sample, showing that the addition of a wax coating lowers the effect the hemp-agar cup has on the liquid in it. Figure 53 shows the conductivity results for all samples. A complete data set of all water quality testing can be found in Appendix D.

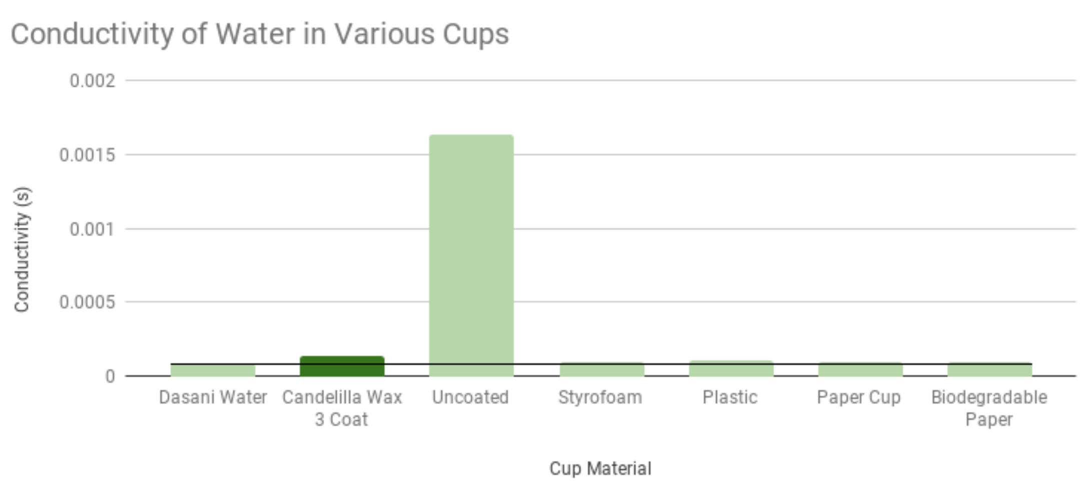


Figure 53: Chart of Samples' Electrical Conductivity

After comparing purified water stored in various mainstream cups on the market to the wax-coated hemp-agar cup, it can be concluded that the candelilla wax coated hemp-agar cup is comparable to products on the market. It is expected that the current materials used for single-use cups have been optimized, and there is little change from the Dasani water to the water in those cups. Thus, with optimization the candelilla wax coat could be optimized to improve results.

6.2 Tensile Testing

Similar to the tensile testing explained prior to analyze the stress related characteristics of the hemp-agar pulp created in section 5.2.2, tensile tests were carried out to compare the new material to its market competitors. Tensile strips based on standard dogbone style were created from the hemp-agar pulp, paper, plastic, and styrofoam and then placed into an Instron 5544. These test results were then averaged and compared amongst each other.

6.2.1 Tensile Testing Methods

Tensile strips made of the hemp-agar material were created in the same manner described previously for tensile testing whereas standardized strips of market competitors were cut from a preexisting cup. Plastic coated paper, biodegradable paper, plastic, and styrofoam samples were tested for comparison. The dog-bone shaped samples created were then placed into the Instron 5544 and tested. Before testing, the strip dimensions were measured with calipers and entered into the software for graphing and calculating purposes. The program calculated the rectangular cross-sectional area of the strips using the equation *area=width*thickness*. Each test was run using the Instron 5544 by slowly applying increasing tensile force to the strip until it breaks or slips. Data from samples that slipped were removed and considered invalid for analysis.

6.2.2 Tensile Testing Results

After testing, the data was analyzed to determine whether the hemp-agar material was comparable to materials used on the market. The Instron 5544 is capable of recording the load applied when the sample material reached its breaking point. This data allowed for the fracture strength of each material to be determined. A comparison of each material can be seen in Figure 54 below. The hemp-agar material is most comparable to the strength of the paper cup and is just under the tensile strength of plastic. Styrofoam was the weakest material tested and showed very low tensile strength. This was predicted due to the structure of styrofoam being small pieces formed together rather than one solid material. It is significant that the hemp-agar material's strength is comparable to product materials currently on the market because consumers will not have to trade off strength for environmental impact.

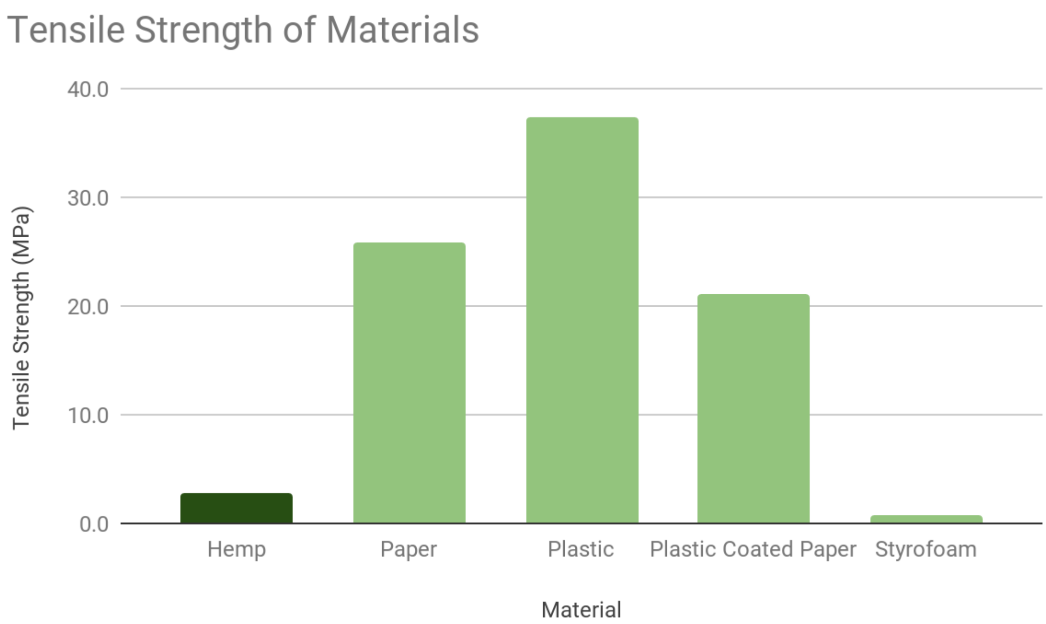


Figure 54: Tensile Strength of Various Materials

6.3 Thermal Conductivity Testing

In order to understand the comparative temperature-based characteristics of the material, thermal conductivity testing was performed. A styrofoam, paper, and plastic cup were tested alongside hemp-agar cup for the comparison. These characteristics are worth observing in a cup since they can affect how long a cup's contents remain hot or cold. It can also provide a better user experience by keeping the extreme temperature insulated from their hand.

6.3.1 Thermal Conductivity Testing Methods

An infrared camera, FLIR A325 30Hz, was placed in front of a four cups of similar shapes and sizes: a paper cup, a plastic cup, an styrofoam cup, and a wax coated, hemp-agar cup. A photo of the setup is shown in Figure 55. The cups were placed on a table in front of the camera and allowed to reach room temperature to avoid any interference from the heat of hands handling the cup prior. Ice water at a temperature of approximately 7 °C was then poured in equal amounts into each cup. The camera then recorded the exterior temperature of the cup to compare the thermal conductivity of the four materials over a 10 minute period. The software provided video footage to analyze the temperature anywhere within the image at a given point in time.

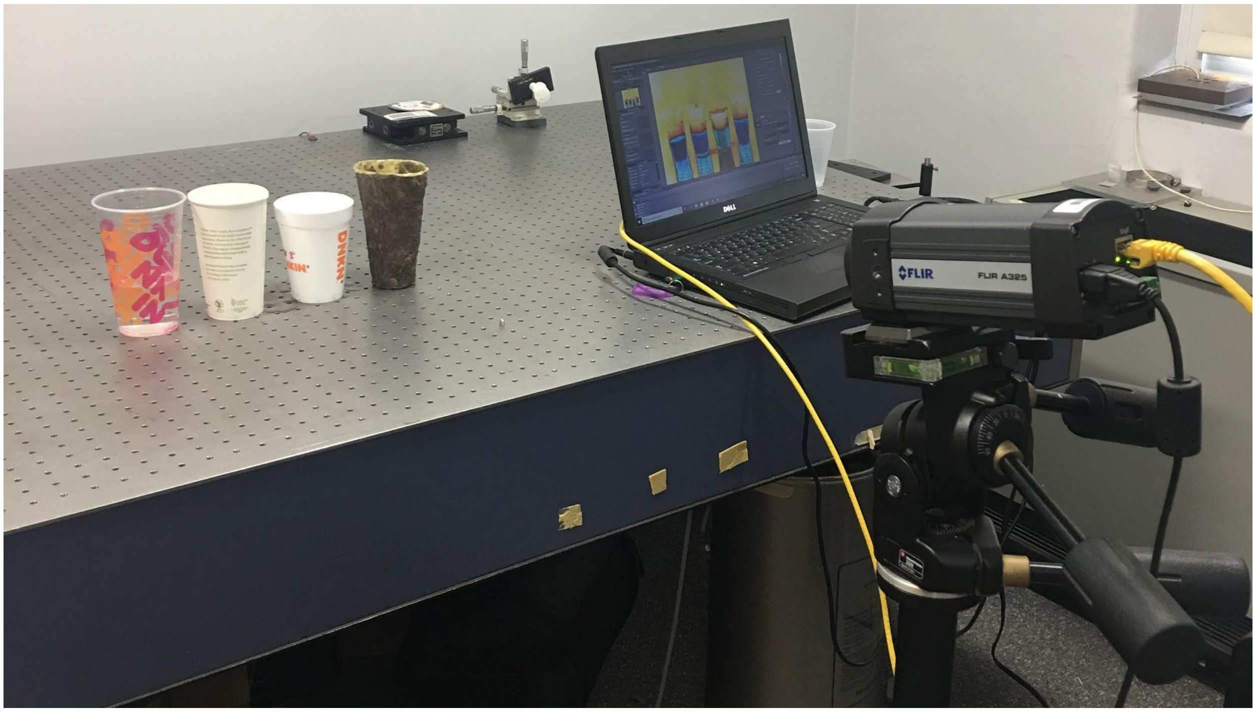


Figure 55: Setup for Thermal Testing

6.3.2 Thermal Conductivity Testing Results

Initial data shown in Figure 56 showing the cups prior to the addition of the ice water were compared to the final cup temperatures after 10 minutes in Figure 57. At the start of the test, the plastic cup appeared cooler than the other three, as shown in Figure 56. This difference is due to the emissivity of the plastic. The emissivity should be corrected for in the test for a better reading than Figure 57. The correction to account for the plastic's different emissivity was not conducted due to time constraints. As a result of this, the cups in Figure 57 shows a reading that is cooler than it should for the plastic cup due to the emissivity. Additionally, it should be noted that in Figure 56, there is a reflection being cast on to the metal test table, this is again due to the emissive nature of the metal table. Figure 57 shows the cups after containing the ice water for 10 minutes. Each figure has a different color scale shown on the right of the figures. In the images, the differing coloration on the table is from reflection and can be ignored when viewing the figures. The coldest parts in the image were at the top of the water line due to the ice floating in the cups. As shown in the images below, the plastic cup started off at a lower temperature due to emissivity related to the material. The data still shows that plastic was the worst insulator, and styrofoam was the best. Though the paper and the hemp agar were similar, the hemp-agar cup performed better.

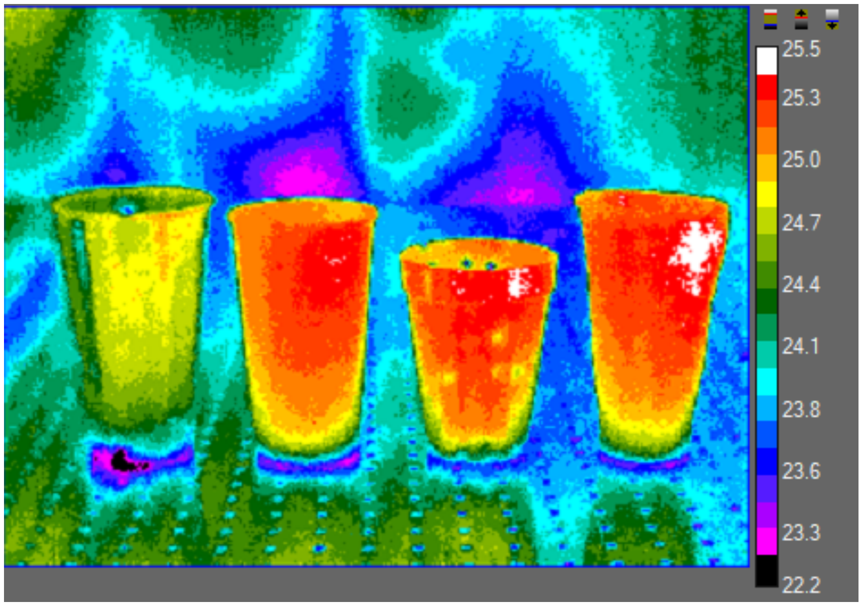


Figure 56: (Left to Right) Plastic, Paper, Styrofoam, and Hemp-agar Cups without Water Added, Temperature(°C)

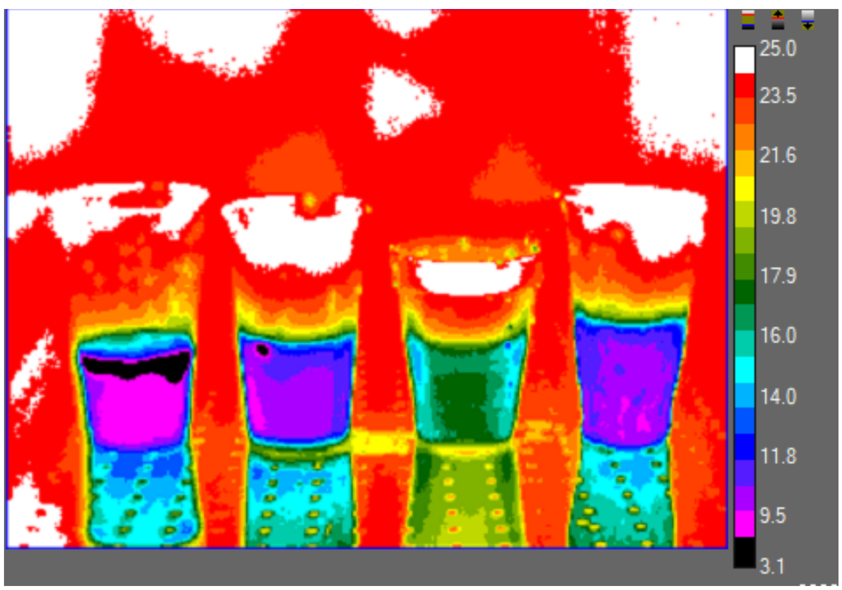


Figure 57: (Left to Right) Plastic, Paper, Styrofoam, and Hemp-agar Cups with Water Added After 10 Minute Period, Temperature(°C)

7.0 Market Analysis

To conduct the market analysis, two separate analyses were carried out: a PESTEL analysis and Porter's Five Forces model. These analyses highlight the market from a broad perspective to better understand the tableware industry. Using these analyses allowed for the development of a realistic sense of the scope of the market.

7.1 PESTEL Analysis

A PESTEL analysis explores the environment in which a particular industry exists. Six factors are considered and studied in depth. These factors are the lens with which the market can be observed. They are: Political, Economic, Social, Technological, Environmental, and Legal. These factors are outlined in Figure 58 (Oxford, n.d.).

Figure 58: PESTEL Analysis (Oxford, n.d.)

7.1.1 Political Factors

Political factors within a PESTEL analysis focus on the politically oriented influences of a market. This includes the political influence associated with lobbyists, focus groups, and individuals. The hemp-agar cup is tied into the political lens to an extent. Due to its strong environmentally-friendly position, it has the potential to be championed by groups that advocate for environmentally oriented policy. Additionally, powerful environmental coalitions that have had a substantial impact on other markets already exist and use their power to enact change at the market level. For example, the World Business Council for Sustainable Development placed Asia Pacific Resources International (APRIL) on probation for their excessive deforestation, causing APRIL to adjust their activities to be more sustainable (Laurance, 2014). This showcases that an organization dedicated to influencing policy and change has the power to make an industry more environmentally friendly. The hemp-agar cup will have support from groups that want to enact positive environmental change.

7.1.2 Economic Factors

Economic factors analyze the economy of a given industry. The disposable cup market is largely influenced by rising fast food consumption and the on-the-go lifestyle. As of 2019, the current estimated value of the disposable cups market worldwide was $14.19 billion and set to grow to $21.2 billion by 2026 as shown in Figure 59 (Statista, n.d.). In 2016, more than 500 billion units of disposable cups were sold across America. Current estimates suggest that number will increase to 850 billion units by 2026 (PR Newswire, n.d.).

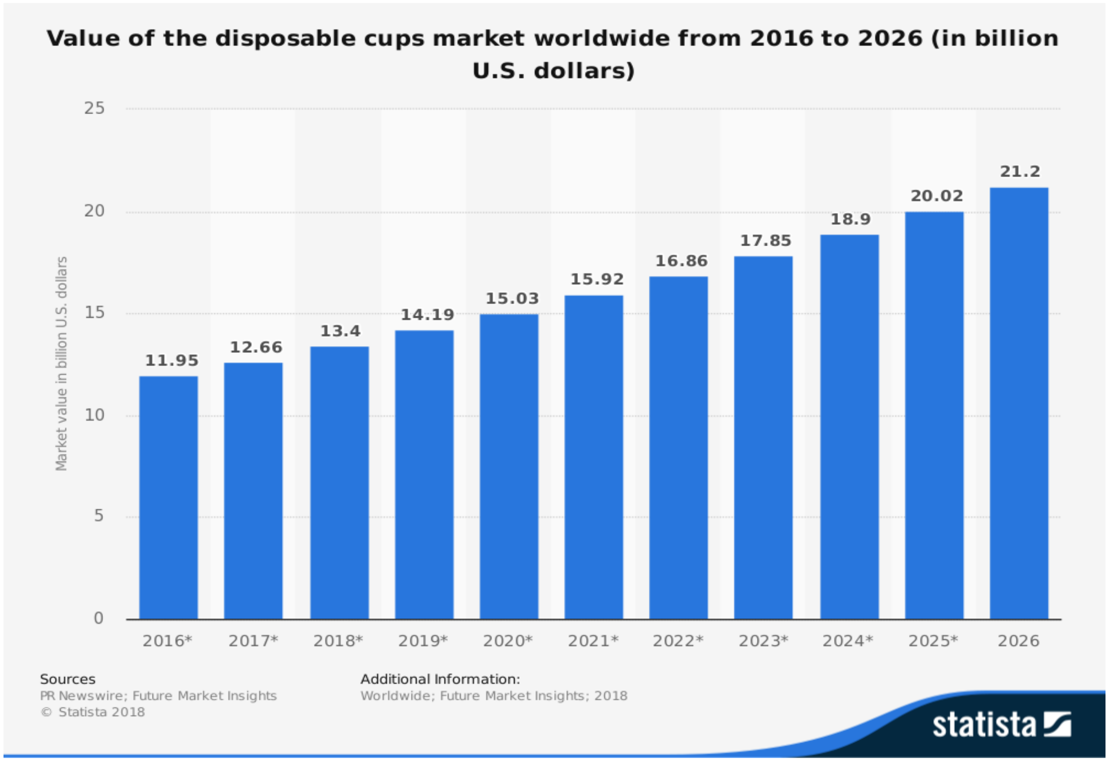


Figure 59: Disposable Cup Market (Statista, n.d.)

7.1.3 Social Factors

Also known as socio-cultural factors, social factors seek to understand the opinions and culture of a given industry. Social factors in this case are influenced by the popularity of the single-use tableware market in addition to the culture of being "environmentally-friendly." As explored via economic factors, there is a popular consumer interest in disposable cups. Additionally, as explained by Roesler, consumers are choosing to purchase more environmentally friendly products (Roesler, n.d.). Meaning that companies who act as customers within the single-use cup industry are moving toward environmentally friendly choices to keep up with consumer trends. For example, McDonald's has committed to eliminating any foam packaging or packaging that contributes to deforestation by 2020 (Geier, 2018). Socially, there is a market space for biodegradable single-use cups.

7.1.4 Technological Factors

The current single-use cup industry is dominated by plastic, paper, and styrofoam. These three players are all mass produced with highly efficient automated systems. These automated systems currently are not transferable to the biodegradable cup. The processes are too imprecise to be transferred to the careful production process of the hemp-agar cup. There is ample opportunity to create new technology that aids in the creation of the cup.

7.1.5 Environmental Factors

Due to the environmentally focused nature of the cup, the environmental factor within the PESTEL analysis strongly favors the cup over other industry competitors. The cup is primarily sustainably sourced from algae and plant matter. Additionally, all waste created from the process is biodegradable, similar to the final product. The only impact that has potential to be negative is the required energy to produce. The product needs heat to be cooked, baked, and coated. These required heating processes consume energy in a non-sustainable way, but require further research to be precisely quantified.

7.1.6 Legal Factors

Different from political factors, legal factors come from policy and laws that have been enacted. Currently, no specific laws exist regarding the use of disposable cups. However, in recent years, American policy has begun to turn its attention to the environment. For example, consider the governmental influence on the use of plastic bags in America. Across the country, two states have completely banned their use, and over 300 counties, cities, and towns have enacted their own bans or fees for the use of plastic bags (Nace 2018). In contrast, ten states have enacted preemption laws that prevent local governments from creating legislation that would limit the use of plastic bags (Nace 2018). It is possible that cup based legislation in support of the hemp-agar cup may be enacted in the near future.

Additionally, policies have already been passed that will aid in the development of the hemp-agar cup. At the end of 2018, the Farm Bill was passed by Congress, which included the removal of hemp from the FDA's controlled substances list (Stein 2018). Formerly, hemp could only be purchased from suppliers outside of the United States. However, with the removal from the controlled substance list, it will be legal to grow and distribute hemp on US soil. This means that the hemp-agar cup will not have to deal with importation tariffs on hemp

7.2 Porter's Five Forces

Porter's Five Forces is a financial model created by Michael E. Porter. This analysis is used to understand the competitive nature of a particular market. A chart showing the different forces is shown below in Figure 60. The five forces that will be analyzed are those from the suppliers and the buyers, the threat of new entrants and substitutes, and the existing competition in the industry (Kenton, 2019).

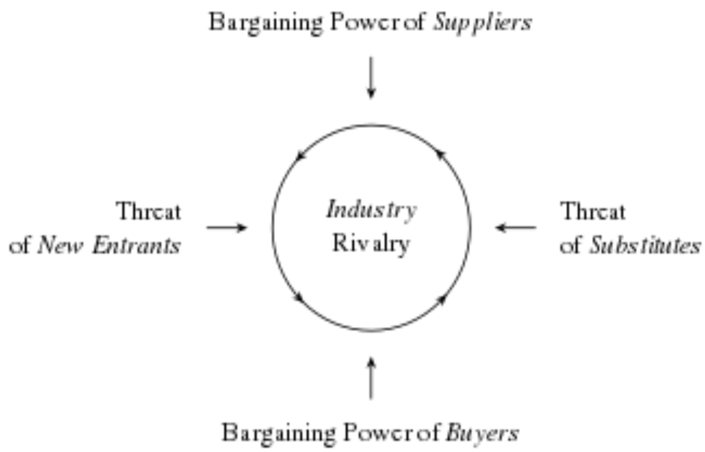


Figure 60: Porter's Five Forces (Fadeev, 1985)

7.2.1 Bargaining Power of Suppliers

There are two main categories of materials that are used to manufacture the hemp-agar cup: materials that are easily accessible and materials that are more specialized. In considering the materials that are easily accessible, corn starch, corn syrup, and lemon juice, many different suppliers are available. They are common food additives, so the bargaining power of these suppliers is relatively low. If a supplier threatens an increase in prices or a drop in quality, there are a great number of alternate suppliers available. These materials are also available from American suppliers, which eliminates the need for importation.

Conversely, specialized materials like agar, hemp, and candelilla wax are difficult to obtain. Even within the scale of this project, these materials needed to be ordered from specialized vendors or purchased at particular stores. It would be necessary for the cup manufacturing process to also involve the growing and harvesting of agar from red algae. Additionally, as discussed in Section 7.1.6, the growth of hemp was not legal in the United States until recently. More businesses are expected to emerge that grow and sell hemp now that it is no longer considered a controlled substance. However, there is still an opportunity for a dedicated farm for production of hemp for the cup. Lastly, candelilla wax is derived from a specific plant so the supply market is very narrow. The production of the wax inhouse with the cup is unrealistic, so this is the greatest obstacle in the supply chain. Alternatives to candelilla wax can be explored, but the suppliers do hold a considerable amount of power.

7.2.2 Bargaining Power of Buyers

The consumers of the cup are individuals and organizations that distribute cold beverages. Individuals have the power to choose an alternative to the cup any time they purchase single-use cups. Larger organizations, like restaurants or campuses, however, have slightly less power. If they choose to enter a contract agreeing to use a particular cup, they will not be able to readily exit that. They do have power when choosing a type of single-use cup. There are many options on the market to choose from. Those options are also going to have much more competitive prices due to their cheaper material costs. However, if a company is mandated to use environmentally friendly cups, the biodegradable cup is the best option.

7.2.3 Threat of New Entrants

The disposable cup market is not difficult to enter. There are no patents for a basic cup shape, and as this project demonstrates, many different materials can work for that shape. The industry is open to new competition. The question for this competition becomes, how will a new entrant manage to scale up their product to become competitive. It is the same problem that the hemp-agar cup will face, however it does have the added advantage of being fully biodegradable and sustainably sourced. It is an easy market to enter, but a difficult one in which to succeed.

7.2.4 Threat of Substitutes

The most obvious substitute to a fully biodegradable cup cup is a easy to clean, reusable one. Both have a similar market: individuals who are mindful of their environmental impact. Additionally, a reusable cup is also more economical in the long run. Compared to its single-use counterpart, the reusable cup will pay for itself after several uses. However, the hemp-agar cup does have the advantage in the restaurant market. Restaurants that provide an on-the-go option would not be able to offer their own reusable cups, so they are less likely to use that as a substitute.

For the individual consumer, the cost to switch to a substitute of single-use cups is minimal. The only associate financial cost is that of a reusable cup as discussed before. However, there are other non-monetary costs that lurk. One of these is the cost of ease of convenience. Single-use cups are a convenient option that require very little forethought or maintenance. A reusable cup, on the other hand, must be carried around and then cleaned after every single use. If a consumer is not willing to take on that extra effort, they likely will not switch to a reusable cup.

7.2.5 Industry Rivalry

This industry has some major players that will not simply give up their strong position. These companies have established brands, become icons, and all but eliminated their costs. Some companies have been advertising their brands for years and have become household staples. Brands like Solo Cup have partnerships with retailers like Starbucks to provide all of their disposable cups (History, n.d.). The specific portion of the industry dedicated to paper cups has a net profit ratio of 14% (Starting, n.d.). Using this figure in combination with the high turnover discussed in Section 4.2.1 of 58 million cups used per year, the paper cup sector of the market is performing very well. Any other competitor would need to build a strong brand and lower costs in order to compete with the existing competition. The hemp-agar cup has potential of developing a strong brand and a strong marketing approach as it is fully biodegradable, an unseen characteristic of its industry competitors.

8.0 Financial Analysis

To conduct the financial analysis,three separate analyses were carried out: a break-even analysis, estimated social cost and a discounted cash flow analysis. These analyses are from the perspective of a full scale production cup manufacturer to understand the financial necessities required to profit from the manufacture of the hemp-agar cups.

8.1 Break-Even Analysis

To calculate the break-even analysis the below formula is used to calculate the required number of units sold to recover costs. This formula will be used at the end of the section after each variable has been explained.

Break-even Sales Unit = Fixed Cost / (Sale Price -Variable Costs)

8.1.1 Fixed Costs

Fixed costs are expenses or costs that are independent of the production output. Examples of fixed cost include rent, utilities, salaries, insurance, and equipment (Kenton, 2018).

The agar-pulp material will require machinery to be manufactured. This machinery would include a cup molding machine, which is assumed to be on average, $30,000. The machine can produce around 2000 cups per hour, requires one laborer to operate, and consumes about 4 kiloWatts per hour (*Guangzhou Dechuang,* n.d.).

8.1.2 Variable Costs

Variable costs are costs dependent on the production output (Kenton, 2019). Therefore, an increase in the number of units created and sold correlates to an increase of the variable cost. The variable costs involved in the manufacturing of a thirty-two ounce biodegradable cup include the manufacturing costs and material cost for agar, hemp, corn starch, corn syrup, lemon juice, candelilla wax, and water. The manufacturing cost includes the machine depreciation, labor cost, and energy cost. Assuming the machine is depreciated at 15% of its value every year, operating at 8 hours a day, 5 days a week, 4,160,000 cups can be produced per year. Assuming the labor cost for the operator is $18 per hour, the cost for operating the machine is $37440. Assuming the cost of energy per kiloWatt hour is $0.11 with the energy used per year by the machine being 8320 kWh (Jiang, 2011). The total manufacturing cost per cup is ($4500 + $37440 + $915) / 4,160,000 = $0.01 per cup.

One thirty-two ounce cup requires 17 grams of agar, 2.06 cups of water, 12 grams of hemp, 1.33 tablespoons of cornstarch, 0.1 gram of candelilla wax, 1.33 tablespoons of corn syrup and 0.67 teaspoons of lemon juice. The price of the materials at wholesale prices and manufacturing cost per cup to determine the variable cost is listed below in Table 9 (*Manufacturers, Suppliers & Products in China, n.d.*).

Table 9: Cost to Produce

	Price of Material	Price Per Unit ($)
Fixed Costs		30,000
Variable Costs		0.32
Manufacturing Cost		0.01
Agar	$0.01/gram	17 * 0.01 =0.17
Hemp	$0.01/gram	12 * 0.01 = 0.24
Corn Starch	$0.0082/tbsp	1.3 * 0.0082 = 0.007
Corn Syrup	$0.009/tbsp	1.3 * 0.009 = 0.013
Lemon Juice	$0.01/tsp	0.67* 0.01 = 0.004
Candelilla Wax	$0.0001/g	0.0001
Water	$0.00009375/cup	3 * 0.00009 = 0.000281
Sale Price		0.50

Below is the formula used to calculate the number of units required to be sold to recover costs. This break-even analysis shows the cups will start making profit after 219,445 cups are sold.

Break-even Sales Unit = 39,500/(0.50 -0.32) = 219,445 cups

8.2 Estimated Societal Cost

To calculate the estimated societal cost of the hemp agar cup in comparison to current market leading competitors: plastic, paper, and styrofoam. The following was considered, the material based production carbon emissions and the cost of disposing each cup into a landfill. According to the Stanford News, the social cost of carbon is $220 per ton or 0.01 per gram (Than, 2017). The average cost to landfill municipal solid waste per ton in the United States as of 2018 is $55.11 (Szczepanski, 2018).

Paper cups produces 109 grams of air pollutants and adds 10.1 grams to landfill per cup (Hocking, 1991). Styrofoam cups produces 32 grams of air pollutants and each cup add 4.7 grams to landfill per cup (Hocking, 1991). A plastic cup produces 9 grams of air pollutants and adds 10 grams to landfill. This means that when a paper, styrofoam, or plastic cup is produced, there is a societal cost of $1.09, $0.32, $0.09, respectively.

8.3 Discounted Cash Flow Analysis

A discounted cash flow analysis will determine the present value of the company based on the future projections. To complete a Discounted Cash Flow Analysis, the first step is to calculate the WACC (Weighted Average Cost of Capital), this is referred to as the company's weighted borrowing rate. The WACC will calculate the incremental cost of debt financing, as the company will require financing to cover continued research and development and initial costs for manufacturing the cups. The calculations assumed the following, a loan rate of 9.75% (for a loan under $25k) and tax rate of 15%, based on a conservative estimate of the first year income being lower than $50,000. In order to calculate the after-tax rate, the tax rate (15%) was subtracted from one and multiplied by the loan rate (9.75%). The weight used to calculate the WACC was 100% as debt financing would solely be used. Once the after-tax rate was calculated, it was multiplied times the weight making the WACC equal to 8%. See the values in Table 10 below.

Table 10: WACC

Debt	Formula	
	Loan Rate (l)	10%
	Tax Rate(tr)	15%
	After Tax Rate	8%
	Weight	100%
	Weighted After Tax Rate	8%

In the next step of completing the discounted cash flow analysis we created projections using a conservative growth rate of 3% over five years. Each year the amount of cups sold increased by 3% over the prior year's amount. In addition, three different sale forecasts were selected for Year 0, each having a probability of 33%. Discounted future values were applied in Years 1-5, using the WACC of 8%, to calculate the present value of each year. Year 0 is represented as the current year and at present value, therefore it does not need to be discounted.

In the projection 1, it was assumed that 250,000 cups were sold during year 0 with the growth rate of 3% in sales, the total present value of $77,622.03. See Table 11 below for full calculation.

Table 11: Projection 1 Discounted Cash Flow Analysis

Projection Annual Growth - 3% / Year 0 - 250,000 Cups Sold						
Year	0	1	2	3	4	5
Projected Cash Flow	$ 45,000	$ 46,350	$ 47,741	$ 49,173	$ 50,648	$ 52,167
Present Value	$ 105	$ 42,917	$ 40,930	$ 39,035	$ 37,228	$ 35,504
Net Present Value	$ 195,718					
Initial Cost	$ 39,500					
Probability (33%)	$ 77,622.03					

In the projection 2, it was assumed that 300,000 cups were sold during year 0 with the growth rate of 3% in sales, with a total present value of $90,532. See Table 12 below for full calculation.

Table 12: Projection 2 Discounted Cash Flow Analysis

Projection Annual Growth - 3% / Year 0 - 300,000 Cups Sold						
Year	0	1	2	3	4	5
Projected Cash Flow	$ 54,000	$ 55,620	$ 57,289	$ 59,007	$ 60,777	$ 62,601
Present Value	$ 105	$ 51,500	$ 49,116	$ 46,842	$ 44,673	$ 42,605
Net Present Value	$ 234,841					
Initial Cost	$ 39,500					
Probability (33%)	$ 90,532.50					

In projection 3, it was assumed that 350,000 cups were sold during year 0 with the growth rate of 3% in sales, the total present value of $271,598. See Table 13 below for full calculation.

Table 13: Projection 3 Discounted Cash Flow Analysis

Projection Annual Growth - 3% / Year 0 - 350,000 Cups Sold						
Year	0	1	2	3	4	5
Projected Cash Flow	$ 63,000	$ 64,890	$ 66,837	$ 68,842	$ 70,907	$ 73,034
Present Value	$ 105	$ 60,083	$ 57,302	$ 54,649	$ 52,119	$ 49,706
Net Present Value	$ 273,964					
Initial Cost	$ 39,500					
Probability (33%)	$ 103,442.98					

Summing the net present values of each the projection by their respective probability of 33% results in a NPV of $271,598.

9.0 Conclusions

9.1 Conclusions from Axiomatic Design Process

In using an axiomatic design process, it was discovered that the attempted product was going to be very difficult to develop. The decomposition resulted in a matrix that was coupled along both axes in such a way that reordering would not resolve the coupling. An example of this unsolvable coupling is that the DP, "Material that maintains its structural functionality for duration of use" directly conflicted with the FR, "identify material that decomposes after use," in the way that using steel as the material would fulfill the DP, but not fulfill the FR. Conversely, the DP "material that decomposes" conflicted with the FR "create material that will maintain its structural functionality for entire use," because the DP could be fulfilled by a mixture of leaves and water, but that would conflict with the FR. These two conflicts are just a pair of examples of the couples that caused problems in the decomposition.

Despite the problems associated with the created axiomatic design, they did help reveal that the process of developing this product would entail experimenting with many different materials to see if they could simultaneously fulfill entire sections of design parameters. While this does somewhat step out of the realm of axiomatic design, it was necessary for the product at hand. The axiomatic design was able to act as an informer that provided insight into the necessary parameters and also provided advanced notice of the challenging design process.

9.2 Conclusions from Design

In regards to the design and development of a product, this project outlined how different decisions were made. To begin, this project focused on developing a material that could meet the contradicting axiomatic design. Through research and development, it was found that a base made of agar and hemp with additional food grade and biodegradable additives as well as a highly involved production process would allow for a cup that remained biodegradable, retained structure, remain storable, not affect smell, formed into a cup shape, and remain waterproof. The final hemp-agar cup prior to wax coating is shown in Figure 61.

Figure 61: Dried Cup Form Before Wax is Added (Side and Top View)

The basic design of the cup started with material analysis. Through this testing the final design and recipe were developed. The material was dried using a convection oven as it was determined to have the most efficient drying time and is most effective at completely removing moisture. This recipe and drying process has applications beyond a cup. It is a rigid, water-resistant, biodegradable material, that can be used for food storage, material packaging, or other short term waste-producing needs.

The waterproofing of the cup was best solved used candelilla wax as shown through the various tests conducted. This wax, however, was applied in such a way that would produce varying results. Ideally the cup would have the minimum amount of wax while still maintaining its waterproof characteristics. This was best done via filling the cup with melted wax and slowly coating the inside of the cup by rolling it as the wax is poured out. Using the current application methods, the final cup form with wax is shown in Figure 62.

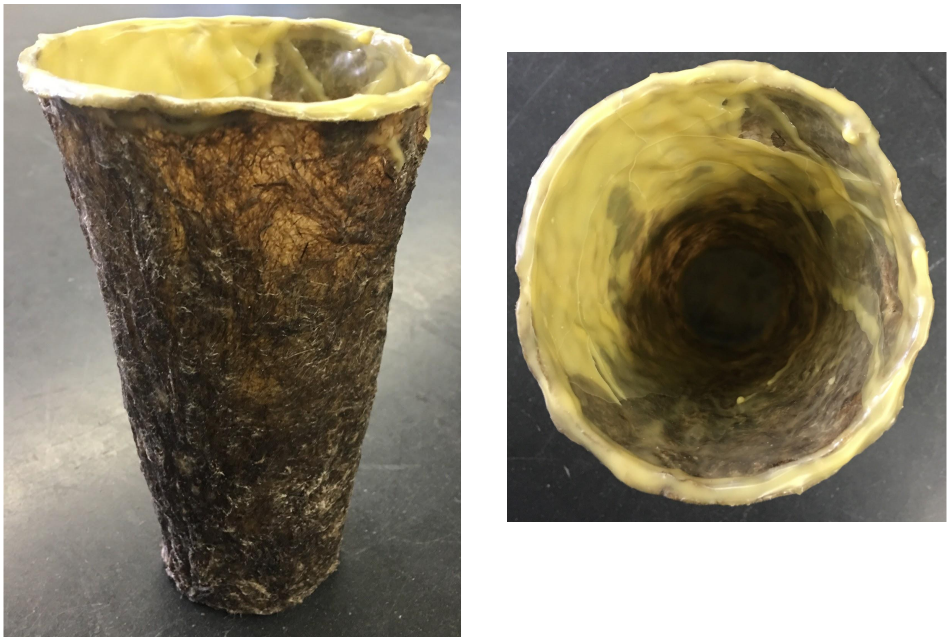


Figure 62: Final Hemp-agar Cup with Wax Coating (Side and Top View)

9.3 Conclusions from Market Analysis

The market analysis provided an in depth study into the industry the cup would be entering. It offered insight into the challenges, competition, and resources available. The takeaway from the PESTEL analysis were factors that can be considered strengths, future strengths, and weaknesses. The obvious strength is the environmental factor, as the hemp-agar cup is designed for the environment. The economic factor also provides a strength as the single-use cup market is vast and well earning. Another is potential for legislation that can aid the distribution and use of the cup. Conversely, legislation that restricts the distribution of the cup is a weakness that stems from legal factors. Other weaknesses are the technological factor. At the moment, no advanced technology exists for the production of the cup. All prototypes were made by hand in a batch process that does not lend itself well to mass production. The future strengths category are factors that can become strengths if they are harnessed properly. The remaining two factors, political and social, fall into this category. A marketing team for the cup would want to focus on tapping into public opinion and powerful individuals to cause chain reactions and vast support for the cup. The benefits of the cup are quite powerful and harnessing that to create a consumer base is a strong opportunity.

Porter's Five Forces provided a model to help understand where the cup would fall in the single-use industry if it were to succeed. The threat of substitutes is low for the cup. The supplier power is only high for three of the raw materials: agar, hemp, and candelilla wax, although if the cup production process were to include the cultivation and harvesting of these materials, the threat from suppliers would be decreased. New entrants into the industry are possible, but only pose a threat specifically to the hemp-agar cup if they have comparable environmental capabilities. As far as buyer power goes, the cup would perform the best if the marketers were to begin their focus on restaurants with carry out options. These large-scale companies often have an interest in remaining environmentally friendly and a contract signed with them would provide a solid source of revenue for the cup. Once this is achieved, the cup would be cemented as a solid competitor amongst the industry rivals. Having even one contract would put it in place next to Solo and Dixie. Once this has been achieved, retail can commence, allowing individual consumers to choose to purchase the environmentally friendly option.

9.4 Conclusion from Financial Analysis

In the financial analysis of the hemp-agar cup, the initial cost to manufacture the hemp-agar cup is greater than its competitors plastic, paper, and styrofoam. However, plastic, paper, and styrofoam all face indirect costs during pre-manufacturing and disposal bearing high costs on the environmental and waste management. This means that when a paper, styrofoam, or plastic cup is produced, there is a societal cost of $1.09, $0.32, $0.09, respectively added to the $0.01 direct manufacturing cost. In comparison, the agar-hemp cups costs about $0.32 to manufacture and are sourced from hemp, a crop that uses less water to harvest than cotton and agar that can be sustainably grown, and contributes no air pollutants from its materials.

Between 2016 and 2018 the average increase in landfill tipping was 7% with the high being in the Midwest at 18.3%. The state of California spends $25 million dollars annually to dispose of plastic waste in landfills (LeBlanc, 2018). If the agar-hemp cups were adopted by 1% of the California's residents, approximately 390,000 people who used a single use cup every day for the year, California could save $272,867 each year, eliminating 4485 tons of water per year. While there remains short term profitability to making paper, plastic, and styrofoam cups, the hemp-agar cup's premium price point offers greater benefit to the environment and society in the long run as the costs of harming the planet become a greater expense.

9.5 Conclusion from Project Management

Traditionally, MQP teams are comprised of students all from the same major, however, this project was unique in combining both management and mechanical engineering students. The combination of these two majors brought knowledge from two disciplines: the mechanical engineering students had the ability to design and construct the biodegradable cup, while the management students had the ability to understand the marketing and financial constructs surrounding single use tableware. The combination of each member's individual expertise and ability to solve problems throughout the project proved to be an extreme benefit. The management students were able to take part in the design process of the experimentation, while the mechanical engineering students were able to understand the financial and marketing portion of the project.

All members of team retained a consistent interest in the project's goal and maintained a high level of accountability with every facet of the project. The team's success can be attributed to the start of our project in which a team charter was constructed. This charter outlined goals of the team and of each individual, as well as established guidelines and policies for every team member to follow. Additionally, teammates had rotational roles, such as a lead and a secretary during advisor meetings. This allowed every member to have the opportunity to assume a different role throughout the project.

The one variable that was difficult to manage during this project was time. During the design phase, time involving the shipping of products to the time needed for conducting tests varied widely. Eventually,once the design phase was concluded, timelines were more predictable and manageable.

10.0 Recommendations

To bring this product to market, several aspects of it would need to be improved like the aesthetic appearance, usability, and mass manufacturability. To improve the appearance of the cup, it would be necessary to add either a thinner coating of the candelilla wax, or an alternative biodegradable coating. It is possible to apply a thin coating of wax using a heated sprayer, however this was not possible within the scope of this project as the cost would have been too high. Additionally, to optimize the marketability of the cup, it should be able to stand high heat to be used for hot beverages. A solution to this may again be sought with advanced technological or material science breakthroughs that was not accessible to this project because of either intellectual property laws and the large associated cost.

In addition to improving the appearance of the cup, more scientific analyses of the cup could further prove the significance and importance of the product. These analyses were not available to this project due to time constraints and the advanced equipment necessary for a degradation and toxicology analysis. While all materials used are biodegradable and food safe on their own, it would be important for future advancements of the project to specifically analyze food grade quality and degradation to improve the overall design and optimization as well as marketability of the cup.

To successfully market and sell this product, it would be necessary to scale up the manufacturing. This would require a factory or automated production system that could produce cups at a high rate. This production system would have a large associated cost consisting of many different factors, meaning a more in depth financial analysis of manufacturing, energy, and labor costs would need to be conducted. This report details the financial costs of the cup, but to really be able to bring the product to the market, expert level guidance would be needed.

Further research and development into other applications of the material that was created for this project can also be explored. Looking into the production process for takeout food containers or freight packaging could produce usable results for other ways to market the product. Deeper exploration into the exact properties of the material would aid in this endeavor and could reveal opportunities for more applications.

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12.0 Appendices

12.1 Appendix A: Initial Design Journal

Title: First day of testing

Date: November 10, 2018

Goal: Preliminary research and to start testing materials to find a method of future testing.

Recipe: Corn husks, maple tree leaves, milk based adhesive, and non-milk based adhesive.

Process: Leaves and husks were dried at 300F for approx 3min.

*Note:they were both slightly wet when put in oven. New husks and leaves were put in at 170 for almost an hour. We dried things on pans in the oven with and without a baking rack trying to keep them flat. We also made rudimentary cup mold out of tinfoil. Paper towels were layered, woven and formed over a cup with the milk based glue.

We tested different combinations of fibers and adhesives to observe how the solid materials and adhesives interacted. We mixed them directly in with the adhesives, layered the solids with the adhesive between them, and attempted to heat press only the material into a mold.

Pictures:

Figure 1: *Leaf and cornhusks partially dried from oven. Rudimentary mold shown in top left.*

Figure 2: *A paper towel soaked in adhesive molded around a cup*

Thoughts: Corn husks cooked in the aluminum mold but dried out at top. Moisture was captured by the tin foil and just ended up steaming the husk at the bottom. To work around this, we put it in a full mold to start then removed the outer cup and cooked it upside down so it would in theory curl around the internal mold portion. Corn husks shrunk far too much when water was removed to be a viable option moving forward. They also curl as they dry, making them even smaller. If dried when flattened or put in a mold, they do not curl as much.

We found that leaves curl significantly and become brittle when dried out. Adding crushed leaf bits to the adhesives did very little in terms of adding strength or form. The only benefit was that in theory we could add enough of it as filler to lower the amount of adhesive we would need. Assuming the adhesive was the more expensive material this could lower production cost. We do not believe leaves would be the ideal material for this, but this concept of price lowering through fillers gave us several ideas of other materials we could test with that would serve this purpose better. Layering the leaves with the adhesive also seems to not give any more benefits than just the adhesive itself. The leaves were once again not strong enough as a material to add any structural benefit to the adhesive

Our first batch of milk based adhesive seemed a bit chunky. We think it's due to waiting too long between adding cold water and hot milk. It seems more usable when it is applied thinly. It is not as jelly like. Milk based adhesive remains tactile and jelly like when thick. Picks up dirt easy due to it being slightly tacky from gelatin. Gelatin has a very strong negative odor that is only partially hidden by mint extract.
Glycerine adhesive melts in hand after a while of holding.

Date: November 18, 2018

Recipe: 3 teaspoons of agar, 2 cups of water

Goal: see how agar forms

Process: found this recipe for agar that is used in food/desserts. Soak the agar in water for half an hour. Mix together on high heat until boiling, boil until dissolved and incorporated. Pour into molds and let cool

Pictures: -

Thoughts: These molds came out very much like jello as they were supposed to be like food. Promising because they became solid, but not solid enough

Date: November 20, 2018

Recipe: 1 cup of agar, 2 cups of water

Goal: To see if agar mixture can be made harder

Process: Soak the agar in water for half an hour then boil on high heat until completely dissolved and incorporated.

Pictures: -

Thoughts: this batch came out much harder than previous. Though this batch did begin to mold within a week.

Title: Pasta Cup

Date: November 22, 2018

Goal: To see if a pasta based cup can function well.

Recipe: Unbleached all-purpose flour, water

Process: Mixed water into flour and kneaded until we formed a dough. Rolled dough into a thin, flat sheet. Cut dough into small circular pieces and formed it into a cup shape. Allowed the pasta to dry in the cup mold for 24 to 48 hours.

Pictures: -

Thoughts: The pasta cup maintained a rigid shape. One crack formed during the drying process, but the unblemished portions of the cup did not leak water. Some flour particles did come loose and end up in the water that was in the cup. In addition to that, the pasta, when exposed to water for more than 24 hours, began to mold.

Title: Almond Flour Pasta Cup

Date: November 23, 2018

Goal: To make a pasta cup that was completely gluten free.

Recipe: Almond flour, water

Process: Mixed water into flour and kneaded until we formed a dough. Rolled dough into a thin, flat sheet. Cut dough into small circular pieces and formed it into a cup shape. Allowed the pasta to dry in the cup mold for 72 hours.

Pictures: -

Thoughts: The almond flour dough did not have the consistency of regular dough. It was stickier and had a clay-like moldable quality. This made it more difficult to form into a cup shape. The resultant dough was also chunkier and grainier than the regular flour. It also took much longer to dry out the almond flour pasta and was more susceptible to cracking.

Title: Pasta with Agar Cup

Date: November 30, 2018

Goal: To create a pasta cup that holds itself together better and is less likely to crack

Recipe: Unbleached, multi-purpose flour, water, ¼ cup of agar

Process: Mixed agar and water into flour and kneaded until we formed a dough. Rolled dough into a thin, flat sheet. Cut dough into small circular pieces and formed it into a cup shape. Allowed the pasta to dry in the cup mold for 24 to 48 hours.

Pictures: -

Thoughts: The resulting cup was stronger than the pasta cup without agar. However, it was grainier and chunkier and less appealing visually. It also still had the problem of some of the cup dissolving into the liquid in the cup. This ends the pasta testing.

Date: December 3, 2018

Recipe: agar, water, vegetable glycerin, vinegar

Goal: Determine if a glue can be made with agar

Process: Soak the agar in water for half an hour. Mix together all ingredients on high heat until boiling. Boil until agar is incorporated. Pour into molds and let cool.

Pictures: -

Thoughts: This mixture was very hard and mixed very well. Should not grow mold because of the vinegar. Found this from a gelatin glue recipe, replaced gelatin with agar

Title: Cornstarch addition

Date: December 3, 2018

Recipe: Agar, water, vegetable glycerin, vinegar, cornstarch

Goal: Determine if cornstarch thickens the mixture

Process: Soak the agar in water for half an hour. Boil on high heat until fully dissolved and incorporated. Pour into molds and cool.

Pictures:

Figure 1: *Agar cornstarch mixture in puck mold*

Thoughts: The corn starch made this mixture a lot thicker, but it was not incorporated well so there were chunks of the corn starch within the dried out mix. Clumps could not be clearly scene in pucks before drying due to it being opaque.

Title: Cornstarch integration improvement

Date: December 10, 2018

Recipe: Agar, water, vegetable glycerin, vinegar, corn starch (with a small amount of water)

Goal: Determine if the cornstarch can be incorporated better

Process: Soak the agar in water for half an hour. Boil on high heat until fully dissolved and incorporated.

Pictures:

Figure 1: *The agar mixture with cornstarch thickens in the pot and has no noticeable clumps.*

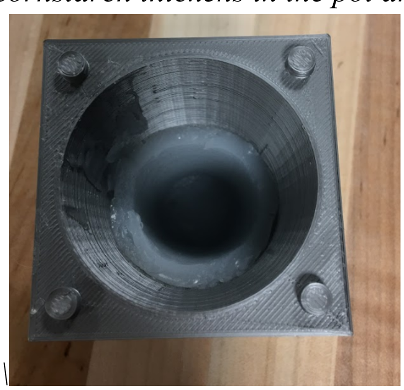

Figure 2: *Initial cup mold half filled with solidified agar cornstarch mixture with top mold portion removed for visibility.*

Thoughts: This batch mixed much better, there were no clumps of cornstarch left

Title: Hemp integration with agar mixture

Date: January 10, 2019

Goal: Determine the best pattern for hemp placement for strength.

Recipe: Various types of hemp with our agar-cornstarch mixture (15 tablespoons of water, 2 teaspoons of vinegar, 2 teaspoons of vegetable glycerin, 1-2 tablespoons of cornstarch.

Process: We used the standard process for making the agar mixture then applied it to the two different hemps in different ways. The combed hemp was spread flat with grain going in one direction (1), stacked with grain going in two directions (2), layered together in a checkerboard pattern (3). The uncombed hemp was spread flat as well (4). They were both layered together on top of each other (5). The combed (6), uncombed (7), and combination (8) were mixed in directly with the agar mixture then poured and spread.

Pictures:

Figure 1: *top left-1, top right-3, bottom left-4, bottom center-2, bottom right-5*.

Figure 2: *top left-6, top right-7, bottom-8*

Thoughts: The hemp need to be fully encapsulated/covered by the agar mixture to avoid the stray hairs sticking out. Mixing the combed hemp directly into the agar mixture fully encapsulates the hemp, but makes it very hard to mix and spread. The hemp strands clump together.

Title: Continued hemp integration

Date: January 14, 2019

Recipe: agar, water, vegetable glycerin, vinegar, corn starch (with small amount of water). 5 cups of cut up combed hemp, another set with uncombed hemp

Goal: Determine how different hemp and mixing in hemp can strengthen the mix

Process: boil on high heat until fully dissolved and incorporated. Mix in hemp with wooden spoon while still boiling, Mix until fully incorporated

Pictures: -

Thoughts: This mixed very well, produced a lot of material. Laid out as a sheet, looks like jerky now.

12.2 Appendix B: Final Agar-Hemp Pulp Recipe

Ingredients:

- Agar
- Water
- Hemp
- Cornstarch
- Corn Syrup
- Lemon juice

*See conversion chart for exact ratios in Appendix C

Steps:

1. Soak Agar

Soak cut agar in water for 30 min to rehydrate, shown in Figure 1.

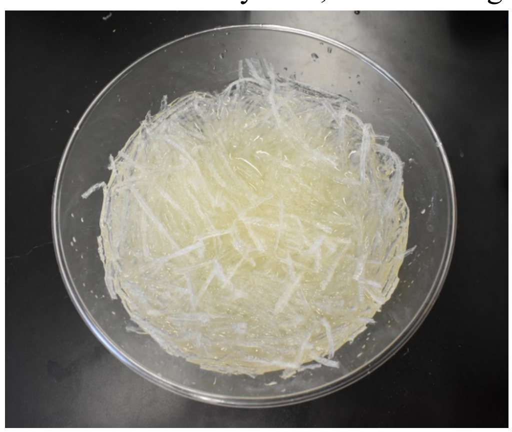

Figure 1: Chopped Agar Soaking in Water

2. Cut Hemp

Cut hemp into approximately 2 cm length pieces, shown in Figure 2.

Figure 2: Cut Hemp

3. Boil Agar

Boil agar and water, stirring occasionally until afar is dissolved completely, shown in Figure 3.

Figure 3: Agar and Water Boiling

4. Mix Cornstarch

Mix cornstarch and a small amount of water together in a separate bowl, shown in Figure 4. Ensure it is thoroughly mixed to prevent clumping.

Figure 4: Cornstarch Mixed with Water.

5. Stir in Liquid Ingredients

Add lemon juice and corn syrup to the agar and mix. Add the cornstarch mixture in small increments while continuously stirring to prevent clumping. Stir until the mixture is slightly opaque, shown in Figure 5.

Figure 5: Boiling Mixture of Agar, Water, Corn Syrup, Corn Starch, Lemon Juice

6. Add Hemp

Sprinkle in the cut hemp incrementally while continuously mixing.

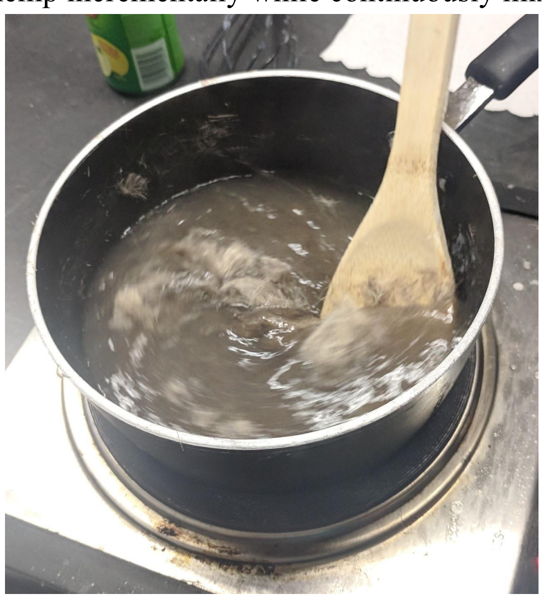

Figure 6: Hemp Added

7. Pour Into Mold

Pour the hemp-agar pulp into the bottom portion of the mold to the fill line then press the top portion in until it can click into place. The top of mold has slots to fit into. Try to prevent large air bubbles from getting stuck in the mold. The mold is shown in Figure 7. Let the hemp-agar pulp cool in the mold.

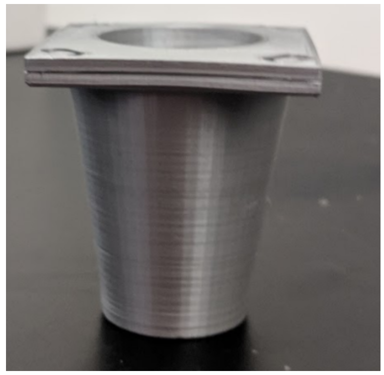

Figure 7: Hemp-Agar Pulp Cooling Mold

8. Remove from Mold

Twist the top portion of the mold to free the hemp-agar pulp then carefully remove the top portion of the mold. Remove the cooled hemp-agar pulp cup from the bottom mold carefully. It might be necessary to run a knife along the outer edge to free the cup from mold. Once freed from the forming mold, place the hemp-agar pulp cups on the drying mold or mesh shown in Figure 8.

Figure 8: Cooled Hemp-Agar Pulp on Mesh Drying Mold

9. Cook

Place the help-agar pulp cups and drying mold in convection at 68°C, shown in Figure 9, for approximately 24 hours or until the cup is dried out and rigid. Dried out samples are shown in Figure 10.

Figure 9: Hemp-Agar Cup Samples in Convection Oven.

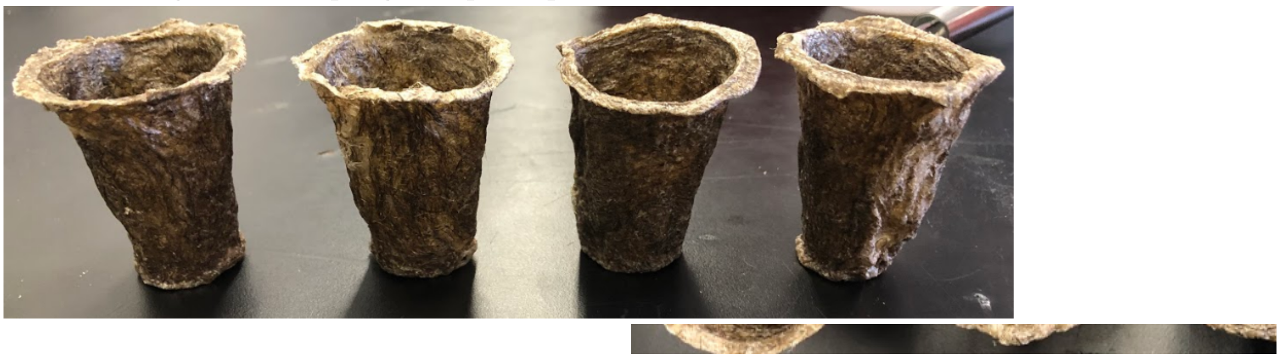

Figure 10: Dried Cup Samples

10. Melt Wax

Carefully melt wax using a double boiler as shown in Figure 11. It is recommended to use wax paper to protect the pot being used from being ruined from wax.

Figure 11: Melted Wax

11. Wax Coating

Pour wax into the hemp-agar pulp cup. Move the cup to roll the wax around the edges then pour out the excess wax. Make sure to coat the lip of the cup while still avoiding the outside walls. Let the cup sit while the wax cools. Figure 12 shows a sample of wax coated cup.

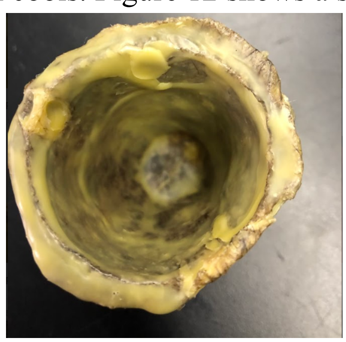

Figure 12: Internally Coated Wax Cup

12.3 Appendix C: Ratio Chart of Recipe

Water (Cups)	Agar (Grams)	Hemp (Grams)	Cornstarch (Tbs)	Water to Cornstarch (Tbs)	Corn Syrup (Tbs)	Lemon Juice (Tsp)	Pulp Created (Cups)
1	8	6	0.7	0.5	0.7	0.3	0.5
2	17	12	1.3	1	1.3	0.7	1
3	25	18	2	1.5	2	1	1.5
4	33	24	2.7	2	2.7	1.3	2
5	42	30	3.3	2.5	3.3	1.7	2.5
6	50	36	4	3	4	2	3
7	58	42	4.7	3.5	4.7	2.3	3.5
8	67	48	5.3	4	5.3	2.7	4
9	75	54	6	4.5	6	3	4.5
10	83	60	6.7	5	6.7	3.3	5

12.4 Appendix D: Water Quality Testing Data

Comparisons of Various Waxes

Wax Coating	Conductivity (s*10^7)	pH	Turbidity (NTU*10^3)
Dasani Water	920	5.7	90
Candelilla Wax 3 Coats	1390	5.5	660
Uncoated	16320	4.5	1690
Candelilla Wax 2 Coats	17660	4.4	2850
Carnauba Wax 2 Coats	22000	4.4	2850
Beeswax 2 Coats	23200	4.4	3270
Nature Wax 2 Coats	22900	4.5	13400
Bamboo Wax 2 Coats	28500	4.3	2280

Comparison of Candelilla Wax to Market Solutions

Material	Conductivity (s*10^7)	pH	Turbidity (NTU*10^3)
Dasani Water	920	5.7	90
Candelilla Wax 3 Coat	1390	5.5	660
Uncoated	16320	4.5	1690
Styrofoam	920	6	230
Plastic	1090	6.3	220
Paper Cup	960	6	360
Biodegradable Paper	940	6.2	80

12.4 Appendix E: Drying Methods Testing Data

Sample Data

Temperature at 68 °C
All weights are measured in grams

Sample	Drying Process	0 Hr	.5 Hr	1 Hr	1.5 Hr	2 Hr	2.5 Hr	3 Hr	3.5 Hr	4 Hr
1	Convection Oven	61	53	49	39	39	37	34	33	32
2	Convection Oven	62	53	50	44	40	37	36	33	32
3	Convection Oven	53	45	41	36	33	30	29	27	25
4	Regular Oven	47	45	42	38	36	32	28	26	25
5	Regular Oven	48	47	43	40	36	32	29	27	27
6	Regular Oven	42	39	36	34	30	29	25	23	22
7	Air Drying	31	31	31	31	31	31	31	30	30
8	Air Drying	40	40	40	40	40	39	39	39	39
9	Air Drying	45	45	44	44	44	44	44	43	43

Calculation of Percent Weight Lost

Sample	0 Hr	.5 Hr	1 Hr	1.5 Hr	2 Hr	2.5 Hr	3 Hr	3.5 Hr	4 Hr
1	13%	20%	36%	36%	39%	44%	46%	48%	52%
2	15%	19%	29%	35%	40%	42%	47%	48%	52%
3	15%	23%	32%	38%	43%	45%	49%	53%	55%
4	4%	11%	19%	23%	32%	40%	45%	47%	51%
5	2%	10%	17%	25%	33%	40%	44%	44%	52%
6	7%	14%	19%	29%	31%	40%	45%	48%	55%
7	0%	0%	0%	0%	0%	0%	3%	3%	6%
8	0%	0%	0%	0%	3%	3%	3%	3%	5%
9	0%	2%	2%	2%	2%	2%	4%	4%	4%

Calculated Averages for Each Drying Method

Method	0.5	1	1.5	2	2.5	3	3.5	4	4.5
Average Convection Oven	14%	21%	32%	36%	41%	44%	47%	50%	53%
Average Conventional Oven	4%	12%	18%	26%	32%	40%	45%	46%	53%
Average Air Drying	0%	1%	1%	1%	2%	2%	3%	3%	5%