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Design of Natural Rubber Extraction from TKS Dandelion

Jehad S. Alrawajfeh
The University of Akron, jsa40@zips.uakron.edu

Trevor Cody
The University of Akron, tac65@zips.uakron.edu

Jason Pogozelski
The University of Akron, jwp32@zips.uakron.edu

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Executive Summary

The global demand for natural rubber is expected to rapidly increase as countries such as China continue to develop, increasing the need for tires and other products. The single economically relevant method for gathering this raw material is from plantations of the Hevea brasiliensis tree. Rubber obtained this way possesses different physical properties than synthetically created rubber that make it much more desirable for use in the tire industry. The availability of only one source of natural rubber has been a well-known bottleneck for years, and this project aims to design a process to supply and extract rubber from an alternative source: the TKS dandelion.

A pilot-scale case of 100 t/y of natural rubber production and a large-scale case of 100 kt/y of natural rubber production were considered. The operations that compose the process were modelled using various assumptions supported by literature. Calculations were performed using software tools such as Microsoft Excel and ChemCAD. A Controlled Environment Agriculture (CEA) 3D greenhouse system that utilizes ebb and flow hydroponics to grow and harvest the dandelions was designed for the pilot-case and scaled up for the larger case. The estimated total installed cost is $118,000,000 for the pilot-scale greenhouse and $118,000,000,000 for the larger scale. The annual operating costs were estimated to total $15,000,000 for the pilot-scale process and $15,000,000,000 for the large-scale process. The products of the greenhouse include the dandelion greens, which are sold as a food product, and the dandelion roots, where natural rubber and inulin may be extracted. An extraction process was designed for the pilot-scale case and scaled up to the larger scale. The estimated total installed cost of the extraction equipment is $811,000 for the pilot-scale and $26,900,000 for the large-scale process. The annual operating costs were estimated to total $27,200,000 for the pilot scale and $54,400,000 for the large-scale

extraction plants. The products from the extraction process are composed of natural rubber, inulin, and glucose. Appendix A contains details for costing associated with the greenhouses, and Appendix B contains details for costing associated with the extraction process.

The pilot-scale process will produce 100 t/y of natural rubber, 400 t/y of inulin, 40 t/y of glucose, and 142 t/y of dandelion greens. This is valued to total $5,800,000 of product. The large-scale process will produce 100 kt/y of natural rubber, 400 kt/y of inulin, 40 kt/y of glucose, and 142 t/y of dandelion greens. This is valued to total $5,800,000,000 of product. The inulin and dandelion greens contribute to 96% of the product value.

Based on operating costs and product values, the proposed process would not be economically feasible. It was identified that the extraction process alone may be economically viable if the value of the feed entering the process, the roots from the greenhouse process, was $15.05/kg. This is not achievable without making major revisions to the dandelion growing process.

The costs associated with growing the dandelions largely outweigh all other costs. For this reason, the priority of future work should be to reduce the growing costs. It is recommended to increase focus on producing dandelions that have a higher yield of natural rubber per root, consider other types of hydroponics, and consider a farming system that utilizes more conventional growing techniques to lower the installed and operating costs of the greenhouse system. Secondary focuses include acquiring better assumptions for future revisions of the design by performing empirical experiments specific to the process and products.

The project required participants to read literature and communicate with experts from fields outside of Chemical Engineering. This improved allowed them to practice their interpersonal and professional communication skills in order to obtain information to better understand the project. The project also exposed participants to the complexity of collaborating with others in other academic institutions offshore by collaborating with student from the IFP School in France. It is hoped that the presented work can be useful in working towards alternative sources of natural rubber to meet future global demand of products important to the citizens of developed and developing nations.

Introduction

Natural rubber is a raw material that has become a staple in products worldwide. The primary product that uses natural rubber is tires, while a smaller portion of the world's production of natural rubber is used to make hoses, rubber balls, gloves, gaskets, adhesives, and many others. Certain properties are found in natural rubber that have never been achieved in synthetic materials. The most unique property that separates natural rubber from synthetic rubbers is the ability to crystallize under strain (Beilen 2007).

Natural rubber is harvested as latex from the hevea tree. Plantations are mainly found in Southeast Asia. A need for the development of alternative sources of natural rubber has been identified due to a growing number of issues involved with harvesting from the hevea tree. It is well known that the hevea tree is susceptible to certain pests and diseases and can only be grown in tropical climates, which is why plantations are limited to only certain parts of the world. The harvesting process is also performed by individuals who must walk miles collecting extracted sap from trees. This inefficient operation is said to offer poor wages and has the potential to promote child labor in certain parts of the world. Due to lack of controls for the growing process the price and quality of natural rubber varies greatly between lots. The demand for natural rubber is foreseen to steadily increase as more countries begin to develop and the demand for rubber goods such as tires increases.

The extraction of latex from dandelion roots has been identified as a potential alternative source of natural rubber (Katrina Cornish, 2016). This project seeks to design a pilot plant that includes a Controlled Environment Agriculture (CEA) 3D greenhouse to grow dandelions and a processing plant to extract rubber and inulin from the roots. A pilot plant with a capacity to produce 100 t/y of natural rubber and a large-scale plant with a capacity to produce 100 kt/y of natural rubber are to be designed and costed. The final products will be natural rubber, inulin, dandelion greens, and glucose.

Background

In previous work, four different alternative sources of natural rubber were identified as potential candidates for supplementing the natural rubber supply chain. Of the sources identified, the extraction of latex from dandelion plants was identified as the overall best choice for a new source of natural rubber. The plant was identified to be suitable for 3D farming and hydroponic culture, reducing the area of land required to grow by using automated greenhouses. Inulin could also be extracted from the plant as another product, which has the promise of a growing market in the food industry.

TKS Dandelion

Taraxacum kok-soghyz also known as the TKS dandelion, rubber root, and Russian dandelion was discovered in the 1930s as a possible source of rubber. The TKS dandelion is known for its production of high quality rubber (Beilen, 2007). TKS was studied and cultivated on a large scale during World War II due to the shortage of rubber from Hevea brasiliensis, better known as rubber trees (Whaley, 1947). Much of the research about the TKS dandelion took place in the Soviet Union; however, there was also research in the United States, United Kingdom, Germany, Sweden, and Spain. During World War II, the highest yield was only 110 kg of rubber per hectare in the United States and 200 kg of rubber per hectare in the Soviet Union (Whaley, 1947). Once World War II ended, the rubber from the rubber trees was once again widely available. Due to the availability of the rubber trees, the research into the TKS dandelion was abandoned.

There has been a revival of research into using the TKS dandelion as another source of natural rubber. This is due to the threats of a rubber shortage from only using the rubber trees. One threat to the rubber trees are diseases and parasites that damage the trees and lead to a shortage of natural rubber (Kirschner, 2012). The labor costs are also reducing the profitability of rubber tree plantations due to the need for every tree needing to be manually tapped to retrieve the latex (Beilen, 2007). Rubber trees are now also being replaced palm oil plantations in order make biofuels (Beilen, 2007). These problems facing the Hevea brasiliensis and the potential of the TKS dandelion are leading to a renewal of the interest in the TKS dandelion as a viable source of natural rubber.

Hydroponics

Hydroponics is the process of growing plants in nutrient rich water system without the use of soil. The roots are either just suspended in air, water, or another medium to help support the roots. Using hydroponics will allow the plant's roots to be in direct contact with the nutrient rich solution. The plant's roots will also have access to the air in many hydroponic applications, which can improve the growth of the plant. Plants grown in hydroponic systems will grow faster and larger than the same plants grown in standard growing in soil (Jones, 2005). This is due to the ease of access to the nutrient rich solution and air. Using hydroponics will also allow for better control of the nutrients in the water and the pH of the water (Jones, 2005). However, one disadvantage of hydroponics is the increased cost and complexity of the system compared to standard growing (Jones, 2005). There are several types of hydroponics including deep-water culture, drip system, nutrient film, ebb and flood, wicking, and aeroponics.

Vertical Farming

Vertical farming is a method of growing crops in vertically stacked layers. Vertical farming takes up significantly less land than standard farming. It also allows the use of controlled-environment agriculture (CEA). CEA is when everything can be controlled in the greenhouse to optimize plant growth, including humidity, temperature, air composition, and light. Many people view vertical farming as the future of farming due to the loss of land available for farming and the increasing need for food in the world (Besthorn, 2013). Vertical farming also allows year-round farming and protection from weather that could negatively affect farming. However, there are many people that doubt the profitability of vertical farming due to the expensive instillation cost of all the equipment and the much greater cost of utilities compared to standard farming (Banerjee, 2014).

Process Design (Experimental Methods)

Greenhouse

Due to the large number of dandelion roots needed to supply the 100 t/y of rubber pilot plant it was determined that there could be potential in designing a new method for growing and harvesting the roots. A controlled-environment agriculture (CEA) 3D greenhouse was identified as a promising method for growing and harvesting the dandelion roots. Using the vertical farming technique will significantly decrease the land needed for greenhouse growing and enable control more aspects of CEA growing that will allow for maximized productivity and quality of the dandelions.

Overall Sizing

The following assumptions were used to determine the area needed to grow the dandelions (Katrina Cornish, 2016):

- Each dandelion root is 20 g dry weight per harvest.
- Each dry root yields 10% rubber.
- The germination stage for the seed would be 35 days.
- The total life span for the adult dandelion plant is 330 days.
- Each dandelion can have its roots harvested 4 times in its 330-day life span.
- The spacing between the dandelions needed to be 6 inches (4 dandelions/ft^2).

The first step in designing the greenhouse was determining how much area we would need to grow the required number dandelions. Table 1 summarizes the number of dandelions that will need to be harvested each year to meet the demand of 100 t/y of rubber. Based on the 375.43 dandelions/ft^2/year and the need for 12,500,000 dandelions, the area for the germination racks would need to be around 33,300 ft^2. The area needed for the grow racks would be around 2,825,000 ft^2 to grow the required number of dandelions per year.

Table 1: Summary of the number of the dandelions that need to be harvested.

	Stage 1	**Stage 2**
Spacing (in)	2	6
Number of Plants / ft2	36	4
Length of Plant Cycle	35	330
Number of Harvest / year	0	4
Total Plants/ft2/year	375.43	4.42
Total Plants/year	12,500,000	12,500,000
Total Harvest/year		50,000,000
Total Harvest/day		136,986
Total Transplants/day	34,247	
Dandelion Roots Harvested/year		50,000,000
Dry Root Mass/Harvest (kg)		0.02
Total Dry Root Mass/year (kg)		1,000,000
% rubber/dry root		10%
Rubber/year (kg)		100,000

Greenhouse Design

There are two types of greenhouse cultivation schemes that influenced the design of the dandelion greenhouse. The first is a vertical greenhouse where there are racks holding multiple shallow tanks using aeroponic or flood and ebb hydroponic irrigation. This allowed for a much smaller footprint for the greenhouse while maintaining a large growing area. Figure 1 shows an example of a vertical greenhouse. However, the disadvantages of this is that the plants are stationary and it would be difficult to automate the harvesting because much manual labor is needed to be able to access all the plants. The next type of greenhouse that inspired the design of the dandelion cultivation is the deep-water culture float tanks used to grow lettuce. In this greenhouse, the seeds are germinated and then placed in rafts that float on the water and are moved to the other side of the float tank as the lettuce grows. This allowed for the germination and planting of the lettuce to take place at one end of the greenhouse and the harvesting of the lettuce to take place at the other end of the greenhouse. This led to a very efficient use of floor space because the lettuce did not need to be collected at many locations throughout the greenhouse; it just needed to be collected in one location. Figure 2 shows a section of the float tank in one of these lettuce greenhouses.

A combination of these two types of design greenhouse cultivation methods lead to a design that would not only decrease the area needed for the greenhouse, but also allow for efficient automated harvesting. The basic idea of the design is that there are racks like in the standard vertical growing technique; however, the plants would not be stationary within the racks. The plants are placed at one end of the very long tanks that are being held by the racks and they would slowly move to the other end on the tank as the plants grow. Eventually the dandelions reach the end of the tank and the roots are harvested. Once the dandelion roots are harvested, they would be placed at the beginning of another rack and the dandelions would move to the other end of the tank as the root of the dandelions regrow. The specifics of how all of this is done will be discussed in more detail in the following sections.

Figure 1: Example of a vertical greenhouse (Image source: trueviralnews.com).

Figure 2: Section of a deep-water culture lettuce greenhouse (Image source: suncrestusa.com).

Process Description

The entire life span of a dandelion plant will last an entire year from when the seed is planted until the roots of the dandelion are harvested for the last time. First, the seed will be planted in a germination rack where it will grow for 35 days and after the 35 days robotic arms will be used to transfer the germinated seed to a hydroponic cultivation raft that will support the plants in the tank. The raft will then be placed at the end of a tank. The raft will then slowly move to the other end of the tank as other rafts at the end of the tanks are being removed for harvesting. Once the raft reaches the end it will be collected and transported to an area where the roots will be harvested. Once the roots are harvested, the same machine used to collect the raft will take the raft to another tank where the process will repeat. Once the root has been harvested for the fourth time the dandelion greens will be removed from the raft. The raft will be reused to plant more germinated seeds, and the process starts again. Figure 3 shows the general layout of the greenhouse and shows the flow of the dandelions through the greenhouse. More detailed descriptions for each of these processing steps will be discussed in the following sections.

Germination and Dandelion Transfer

The first step in the process is planting the dandelion seeds. The dandelion seed will be planted in germination racks where they will germinate for 35 days. The germination racks are a standard size in many agricultural applications. Each rack has 8 levels and each level has 32 ft^2 available for plant growth. To meet the required number of seeds that need to be germinated each year there will need to be 130 germination racks. The racks will be stored in climate controlled rooms where the temperature and humidity to optimize the seed growth. Figure 4 shows an example of how the germination racks are stored.

Once the seeds have been in the germination rack for 35 days they need to be transferred to the hydroponic cultivation rafts. To replace the amount of plants that need to be in the first stage of the grow racks there needs to be 34,560 plants transferred to the rafts and placed into the first stage of the grow racks per day. The number of plants that are being transferred to the rafts and placed in the grow racks need to equal the number of dandelions that are having the roots harvested for the last time. The hydroponic cultivation rafts are 4 feet by 9 feet and can hold 144 dandelions. Figure 5 shows the layout of the dandelions in each raft. The germinated seeds will be transferred to the rafts by robotic arms. Figure 6 shows the robotic arms that will be used to transfer the seeds.

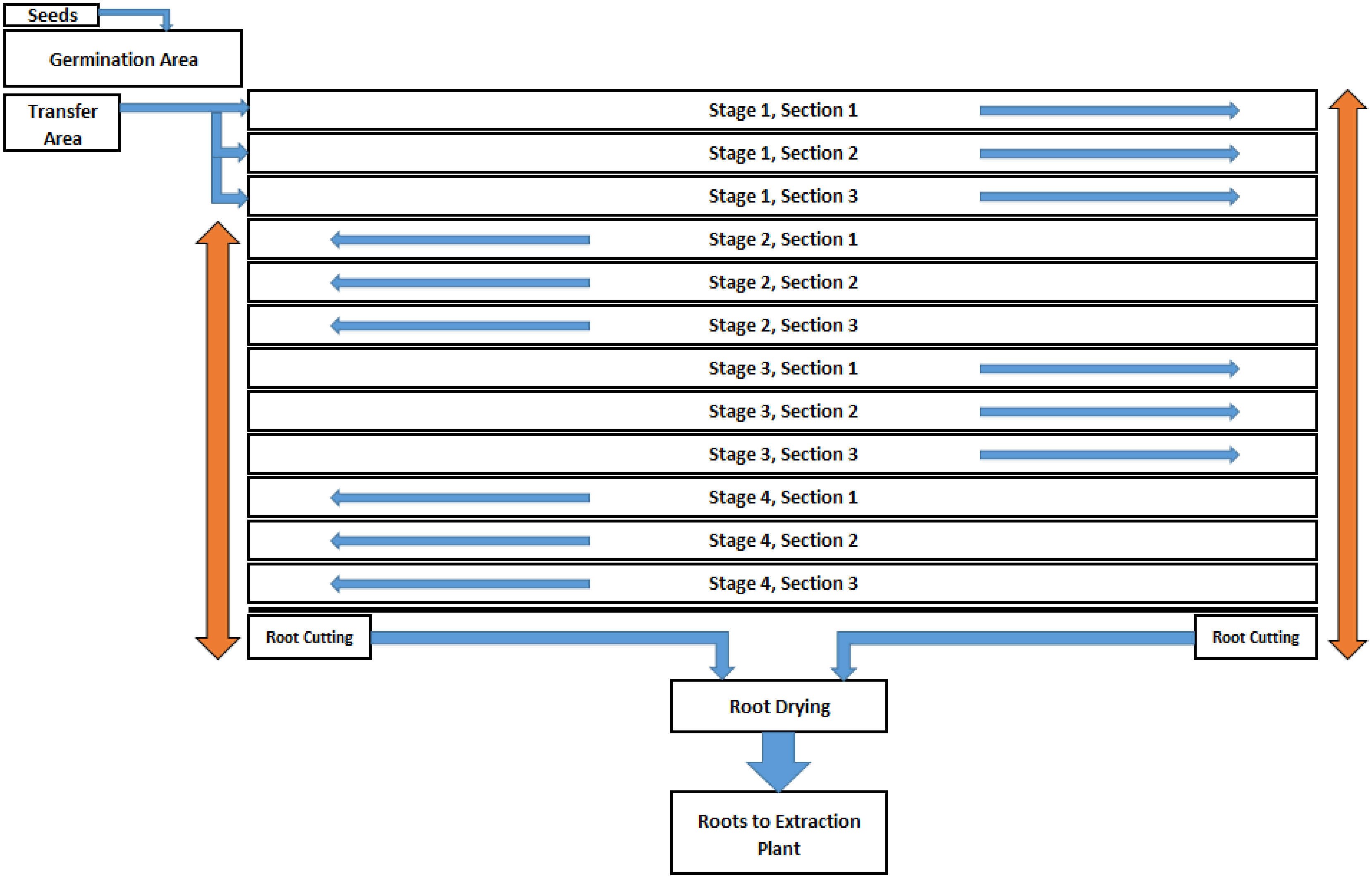

Figure 3: General layout of the dandelion greenhouse (top view). Blue arrows represent the flow of the dandelions through the racks and the orange arrows represent the movement of the machine that will collect the dandelions from the racks.

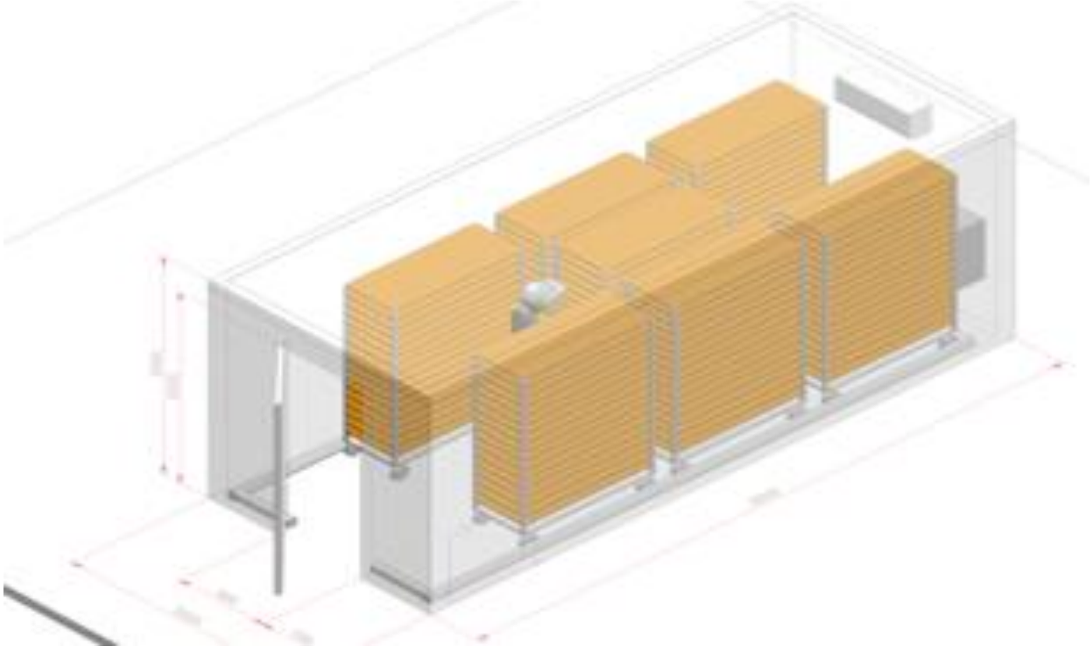

Figure 4: An example of how germination racks are stored.

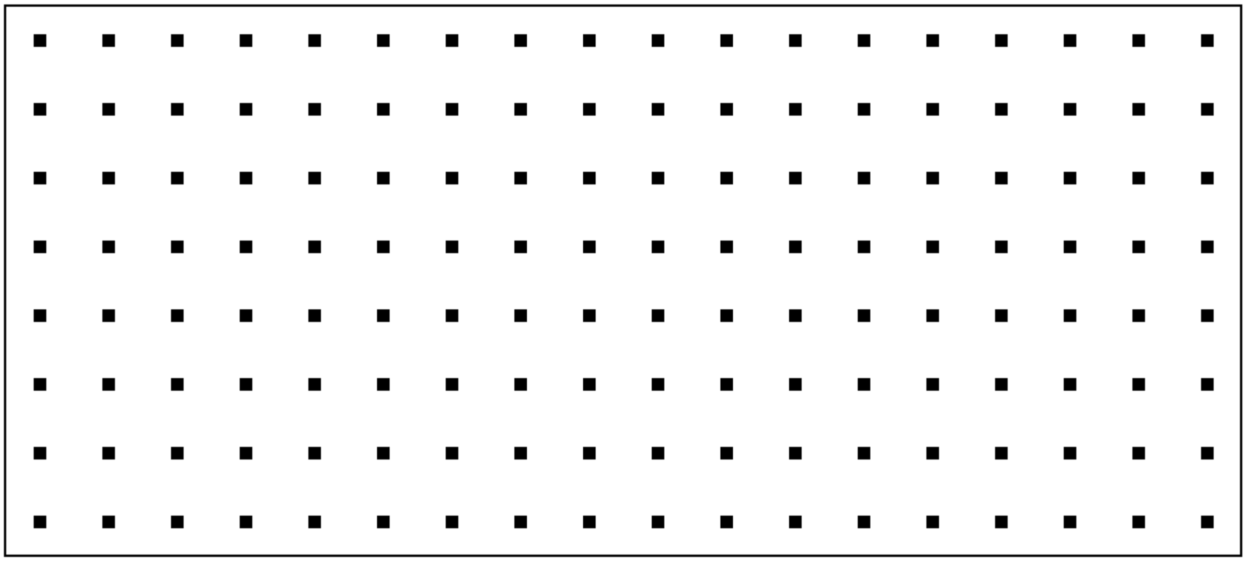

Figure 5: The layout of the hydroponic cultivation rafts. The black squares represent where the dandelions will be held

Figure 6: Robotic arms used to transfer the germinated seeds to the hydroponic rafts.

Grow Racks

The largest and most important aspect of the dandelion greenhouse is the design of the grow racks. The grow racks will provide 2,833,920 ft^2 for growing dandelions and will supply around 50,457,600 dandelion roots per year which is 0.1% greater than the number of roots required per year which will help in the case of unforeseen losses of some of the dandelion roots. The number of dandelions on their first, second, third, and fourth root harvesting will be the same and each of the four stages of harvest will be in different racks. This means each level will have 88,560 ft^2 and each stage will have 708,480 ft^2 for cultivation area. The different stages can be seen in Figure 3. The design for each of the four stages will be the same except for the direction the rafts will flow.

Each stage of grow racks will be made up of three sections with five racks in each section. Figure 7 shows the layout of the racks in each of the three sections within a stage. Each rack is 738-foot long and will hold 16 tanks. The racks are cantilever racks with 4-foot arms to support the tanks. Figure 8 shows an example of the type of racks that will be used to support the tanks. The racks do not need to be built out of any kind of special material because it should never come into contact with water and therefore do not need to be rust resistant.

Each hydroponic tank will be 738 feet long and 4 feet wide. It was determined that the tanks will need to be 18 inches deep when the root in fully-grown (Katrina Cornish, April 2017). However, instead of making the entire tank 18 inches deep the tank will start out only 2 inches deep where the hydroponic cultivation rafts are first placed because of the significantly shorter roots. The depth of the tank will then increase by 2 inches every 82 feet, which will lead to an 18 inch depth where it is needed when the roots are fully-grown. This will significantly decrease the amount of water that will be needed to fill the tanks. If the entire tank was 18 inches deep the tanks would be 4,428 ft^3 and with the new design, the tanks will only be 2,460 ft^3. The tanks will be slightly angled to make draining water from the tanks easier. The tanks will also have rollers on the edge of the tanks that will allow the hydroponic rafts to move the length of the tank. The tanks will be made of white/opaque high-density polyethylene. The tanks need to be white/opaque so light will not be able to reach the interior of the tanks to prevent algae growth in the nutrient rich irrigation tanks. Each tank will be made of 20-foot long segments that will be connected to make the entire 738-foot-long tank. This will allow for easier maintenance in case a section of the tank needs to be fixed.

The hydroponic cultivation racks will support the dandelion plants over top of the tanks so the roots will hang down into the tanks. The rafts will also sit on top of the rollers so they can be moved down the length of the tank. The rafts will be made of white/opaque polycarbonate. This is a stronger material than the tanks are made of. This is due to the rafts needing to be able to support the weight of the dandelions. Each raft is 9 feet long so there will be 82 rafts in each tank at a time.

Each section of grow racks will be roughly 45 feet wide and 738 feet long. There will be five-foot gaps between each section for maintenance purposes and to improve airflow. This will make each stage of the growing racks roughly 145 feet wide. There will also be five-foot gaps between each stage so the overall width of the grow racks area will be approximately 595 feet wide and 738 feet long. This means the floor area required for the growing racks will be 439,110 ft^2, approaching 10 acres or 4 hectares.

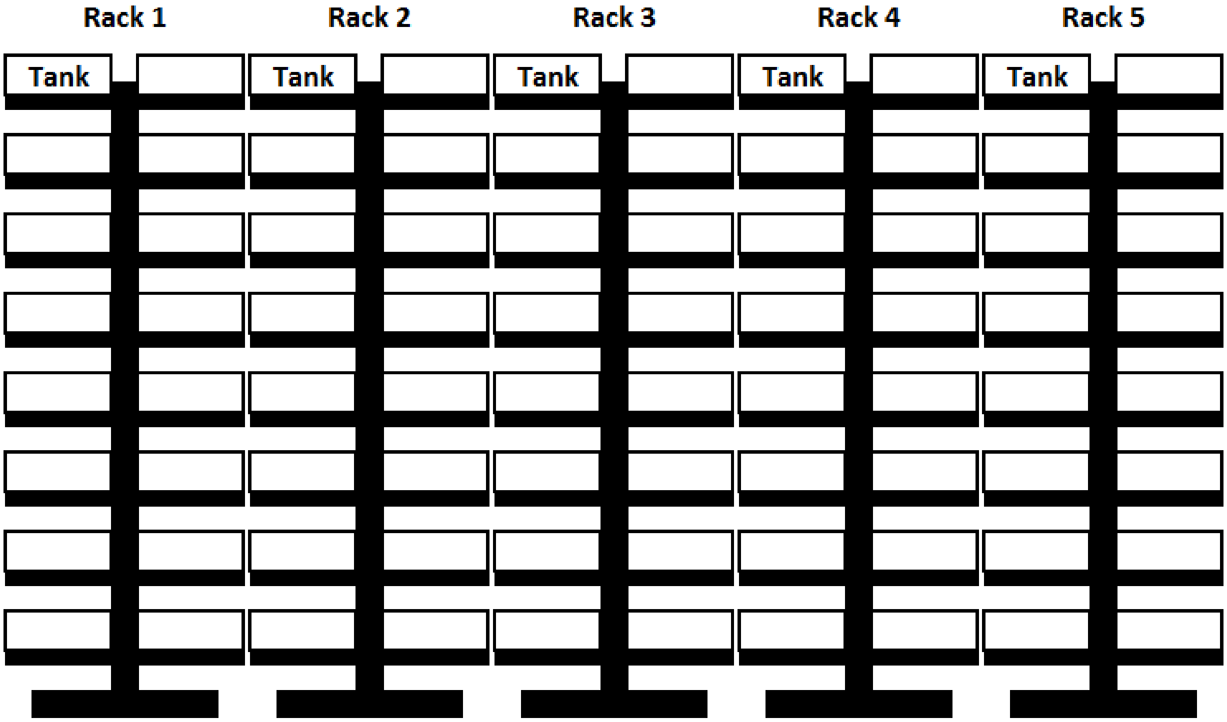

Figure 7: Layout of the racks in each section of a stage.

Figure 8: Example of the type of cantilever racks that will be used to hold the hydroponic tanks.

Hydroponic System

Two types of hydroponics were considered when trying to determine which one would be used in the dandelion greenhouse. They were aeroponics and an ebb and flood system. Aeroponics is when the plants are supplied the nutrient solution through spray nozzles. Ebb and flood is when the tanks are filled with water until the roots are completely submerged and then the water is immediately drained so the roots can have access to air. Both methods are good because they allow the roots to have access to both air and the nutrient solution. It was determined that the ebb and flood method would be the best due to the increased maintenance required for the aeroponic system because of the nozzles clogging. It was also determined that there may be problems with the mist from the nozzles being able to get to the entire root due to the thickness of the dandelion roots.

Once it was decided that ebb and flood system would be used it needed to be decided how the water would be pumped to the tanks. It was determined that each tank needed to be filled every 8 minutes (Katrina Cornish, March 2016). With there being eight tanks in each column it was decided that each column of tanks would be supplied by a single pipe. Figure 9 shows how the piping will be used to supply the entire column of tanks. It works by having the valve open to only one of the tanks and there will be sensors in the tank that indicate when they are full. Once the tank is full, the valve will close on the water supply and the valve to supply the next tank will open. At the same time a valve will open that will allow the full tank to be drained. It was originally discussed to have the water from the tank above drain to the tank below it, but there is not enough information on how much nutrients and water the roots will absorb, which could affect the composition of the water going to the next tank. The tanks will always be filled at the shallow end of the tank and drained at the deep end of the tank. Based on each tank needing to be filled every 8 minutes and it was determined that each tank needed to be able to be filled in 1 minute. The means the flow to the tanks must be 2,460 ft^3 per minute or roughly 18,500 gpm. There are 120 columns of tanks in the growing rack system so that means there needs to be approximately 2.2 million gpm of water being pumped in the greenhouse.

The tanks storing the nutrient solution will be stored in a separate utility building along with the pumps for moving the water. The tanks will be large enough to hold enough nutrient-rich water to fill all the tanks. The tanks will be at a lower level than the rest of the greenhouse. This will ensure that the tanks on the grow racks will be able to drain by gravity. The nutrient solution used for this process will be a Hoagland solution. Table 2 shows all of the components and the concentration of the components of a Hoagland solution. The tanks will be monitored to ensure the composition of the nutrient solution is being maintained.

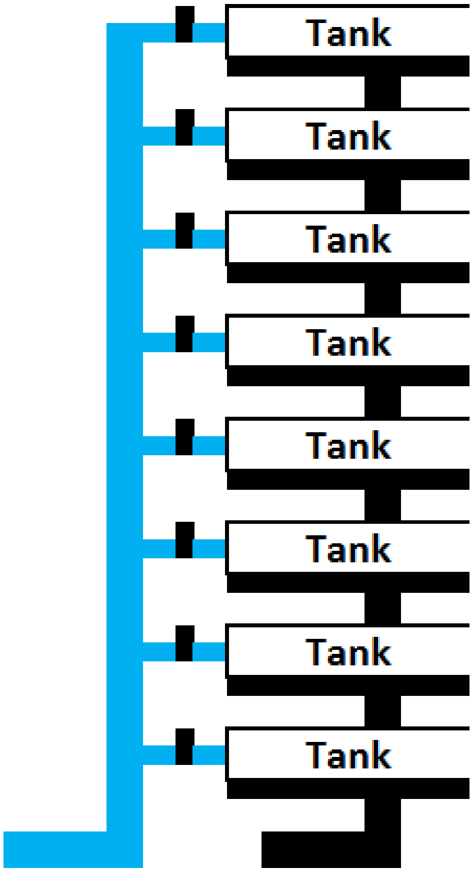

Figure 9: Piping design for each column of tanks in a rack. The Blue lines represent the pipes and the black rectangles of the pipes represent valves.

Table 2: The components of a Hoagland solution (The Origins of Liquid-based, Concentrated Fertilizers; Hoagland's Solution)

Hoagland Solution	
Elements	**Concentration (ppm)**
Potassium	235
Nitrogen	210
Calcium	200
Sulfur	64
Magnesium	48
Phosphorus	31
Iron	5
Boron	0.5
Manganese	0.5
Zinc	0.05
Copper	0.02
Molybdenum	0.01

Dandelion Collecting and Root Harvesting

In order to be able to harvest the roots from the dandelions and to move the rafts from stage to stage the dandelions need to be collected from the end of each tank. The machine that will be used to collect the dandelions will be designed similar to a standard scissor lift. Figure 10 show a scissor lift similar to the one used to collect the dandelions. As opposed to the standard scissor lift the scissor lift used to collect the dandelions will have supports with rollers that will act as an extension of the rollers on the tanks and the rafts will be simply rolled onto the supports of the scissor lift. The scissor lift will be designed to collect the raft out of five tanks at one time. After the scissor lift has the rafts it will move to the root cutting area where the roots will be harvested.

The cutting area will need to be approximately 23 feet wide to harvest the roots from the five rafts at one time. The machine used to cut the roots will be similar to a sickle bar mower. Figure 11 shows a sickle bar mower. The machine used to cut the roots will likely be thinner than the sickle bar mower and will have sharper blades to cut the roots cleanly. However, the sickle bar mower is a good model for the harvesting system used in the dandelion greenhouse. In the actual process of harvesting the roots, the cutting machine will be stationary and the scissor lift will bring the dandelions to the cutting machine. There will be rollers directly above the cutting machine and the rafts will be rolled onto them while the machine is cutting the roots. Once the raft has been rolled completely past the cutting machine and the all the roots have been harvested the raft will be rolled back to the scissor lift and transported to the next stage of the growing racks. Based on the layout of the greenhouse it was determined that it would be best if there were two collecting machines and two cutting machines (one for each side of the greenhouse). The dandelions will need to be collected and the roots will need to be cut in under 15 minutes in order to harvest the necessary number of dandelion roots per day.

Figure 10: The type of scissor lift used to collect the dandelions.

Figure 11: Sickle bar mower that is similar to the machine that will be used to harvest the roots.

Drying the Roots

The final step in the dandelion greenhouse will be the drying of the roots. The roots need to be dried so they can be stored and shipped without the fear of mold or other problems caused by moisture. When the roots are harvested, they are approximately 80% water and they must be dried so the roots are less than 10% water. The roots will be dried using a conveyor oven heated with natural gas. Figure 12 shows an example of a conveyor oven that could be used to dry the roots. The reason for heating the oven with natural gas is that the resulting CO_2 from the burning of the natural gas can be repurposed and used to provide the excess CO_2 needed in the greenhouse. Once the roots are dried, they can be packaged and stored or shipped to the pilot plant where they can be made into natural rubber.

Figure 12: Example of a conveyor oven that could be used to dry the roots.

HVAC and Lighting

Two crucial elements for growing plants are the lighting and the system to control airflow in the greenhouse. The plants need lights to grow and because the greenhouse uses the vertical growing technique, most of the plants will not have access to light from the sun. Therefore, artificial light will need to be provided to the plants in the form of wavelength controlled LED lights. By optimizing the wavelength of the lights plant growth can be improved. Figure 13 shows the type of light that will be used in the grow racks.

Another important element for growing plants efficiently is making sure there is proper airflow throughout the greenhouse. Airflow is important for moving the oxygen generated by the plants away from the plants and providing the plants with fresh, CO_2 rich air to maximize the dandelion growth. The standard for greenhouses is one air change per minute. This means the airflow in and out of the greenhouse must be equal to the volume of the greenhouse. To meet this requirement, the airflow in and out of the greenhouse must be approximately 16.8 million ft^3/min. The composition of the air will be monitored and controlled to maintain the ideal level of CO_2 in the greenhouse.

Figure 13: The type of wavelength controlled LED lights that will be used in the grow racks.

Greenhouse Summary

Table 3: Summary of the area needed for the grow racks.

Floor Area, ft2 (Acres)	439,110 (10.1)
Floor Area, m2 (Hectares)	40,795 (4.1)
Growing Area, ft2 (Acres)	2,833,920 (65.1)
Growing Area, m2 (Hectares))	263,280 (26.3)
Ratio Growing : Floor Area	6.5

Table 3 shows the approximate area of the of the greenhouse compared to the area for growing dandelions in the grow racks. The ratio of area for growing the dandelions and the area of the greenhouse is 6.5, which shows a very efficient use of floor space.

Table 4: Summary of the amount of rubber harvested each year and the amount of rubber harvested per area.

Total Plants/year	12,614,400
Total Harvests/year	50,457,600
Total dry root mass/year (kg)	1,009,152
Total rubber/year (kg)	100,915
Rubber/Growing Area/Year (kg/hectare/year)	3,833
Rubber/Floor Area/Year (kg/hectare/year)	24,737

Table 4 shows the rubber that can be obtained per growing area and the floor area of the greenhouse. The kg of rubber per hectare of 24,737 compares very well to studies that used standard farming techniques as opposed to vertical farming hydroponic method.

Extraction Plant

Process Description

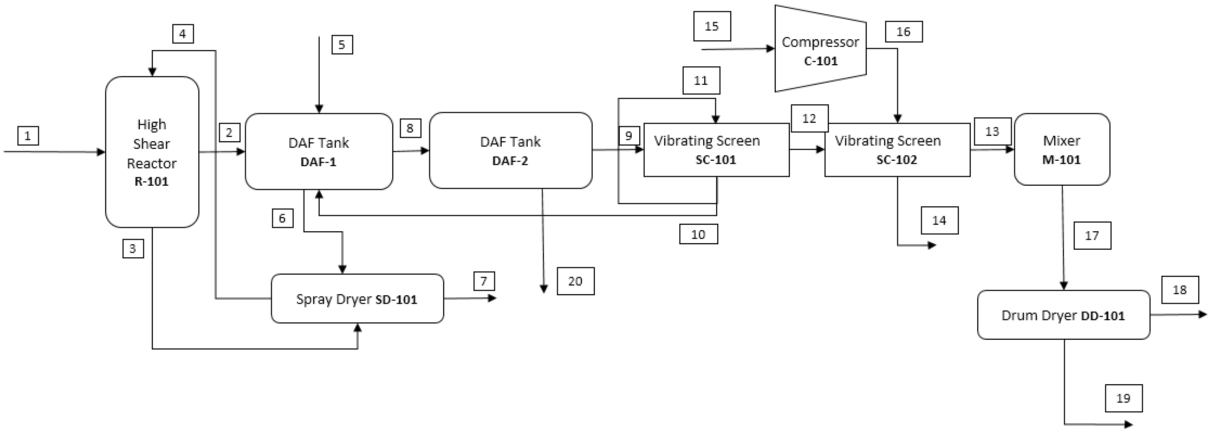

Figure 14. A process flow diagram of the proposed extraction process.

Table 5. Mass flows of the extraction process.

Stream	1	2	3	4	5	6	7	8	9	10
Mass Flow Rate (kg/h)										
Rubber	12.5	12.5	0	0	0	0	0	12.5	12.5	0
Water	25	48.6	74.3	97.5	9.65	23.6	0	49.6	49.6	14.95
Inulin	50	10	40	0	0	10	50	0	0	0
Cellullose	50	50	0	0	0	0	0	45	0	0
Glucose	0	0	0	0	0	5	5	0	0	0
Cellulase Enzyme	0	0	0	0	1	1	1	0	0	0
Air	0	0	0	0	0	0	0	0	0	0

Stream	11	12	13	14	15	16	17	18	19	20
Mass Flow Rate (kg/h)										
Rubber	0.0	12.5	12.5	0	0	0	12.5	12.5	0	0
Water	1.5	12.5	5.4	7.1	0	0	5.4	1.4	4.0	0
Inulin	0	0	0	0	0	0	0	0	0	0
Cellullose	0	0	0	0	0	0	0	0	0	45.0
Glucose	0	0	0	0	0	0	0	0	0	0
Cellulase Enzyme	0	0	0	0	0	0	0	0	0	0
Air	0		0	1.8	1.8	1.8	0	0	0	0

A process flow diagram of the extraction process is displayed in Figure 14, with associated mass flows in Table 5. Dried roots obtained from the farming process are sent to a cone crusher and a rod mill in series. The roots are to be wet grinded. Once the roots are passed through the cone crusher the 15-20cm roots will be ground to roughly 25mm. The 25mm particles are then further ground in the Rod Mill to a size of 2.5mm so they will be suitable for the extraction process.

The ground roots are sent to a high-shear reactor. The reactor is to be fed with 70°C water so that water drained with the products is replenished and 10% of the mass of inlet roots of fresh water is added. It is assumed that roughly 80% of any inulin in the roots will dissolve and with sufficient temperature and pH control the maximum mass fraction of inulin dissolved in water is 0.35 based on findings by Phelps (1964). The dissolved inulin is sent to a spray dryer for further processing, which will be discussed. The remaining components of the roots are sent to a series of dissolved air flotation tanks for further separation.

The extraction and coagulation of the natural rubber from the roots takes place in a series of two dissolved air flotation (DAF) tanks. Both tanks are assumed to have a twenty-minute residence time. A loading of 0.02 g of cellulase enzyme per gram of cellulose entering the DAF tanks is added to the first DAF tank. The interaction between the enzyme and the cellulose helps loosen the cellulose components of the roots from the rubber and creates glucose as a byproduct. Using assumptions based on literature, it was found that at the discussed loading, residence time, and temperature, 10% of the cellulose is converted to glucose (Liu, 2015). It is assumed that any remaining inulin in the process stream is also dissolved in the first DAF tank. The glucose and inulin stream are sent to the same spray dryer as the inulin stream from the reactor for further processing. The remaining process stream consisting of water, natural rubber, and cellulose is fed into the second DAF tank to further coagulate the rubber. The natural rubber is skimmed from the top of the DAF tank and the products are sent to a drying step of the process. Water from the vibrating screens is recycled to the first DAF tank to reduce usage of fresh water.

After being passed through the second DAF tank, the cellulose has been entirely removed, leaving only natural rubber and water. This mixture then passes over two vibrating screens to further remove water and clean the product. Of the water coming out of the first vibrating screen, 10% is recycled and flowed through the top of the screen to help with cleaning. The remaining water is purged. The second vibrating screen passes compressed air over the wet rubber to remove excess water, which is also purged. The rubber is then sent through a mixer, followed by a drum dryer to reduce the water content to 10% before being sent to a rubber block former, where it is baled, packaged, and stored to be sold as a product.

A spray dryer is used to remove the water from the inulin and glucose secondary products. These products are then sent to a different process to be further separated and processed. These additional steps will not be discussed in this report. A portion of the evaporated water is to be condensed to 70°C and recycled to the high shear reactor in the initial stages of the separation process.

Process Design

The following section outlines the steps taken to perform the simulation of the process. Detailed calculations and assumptions for each respective part can be found in Appendix B.

A feed of dried roots is assumed to be provided from the farming step of the process. The length of each root is assumed to be 200mm for the purpose of sizing the cone crush and rod mill. The cone crusher has a reduction ratio of eight (Couper 2012) and was determined to be capable of grinding the roots to 25mm particles. The rod mill has a reduction ratio of 10 (Couper 2012) and was determined to be capable of crushing the roots to 2.5mm particles. The power required for both units was estimated using tabularized data from the Chemical Engineer's Handbook (1988) in order to determine the cost of the crusher and mill.

The high-shear reactor was assumed to require the same amount of power to run as the crushers and grinders combined. The volume was determined using a selected 30:1 water to solids volume ratio. A residence time of twenty minutes in the reactor was assumed and the solids volume was determined by multiplying the volume flow rate by the residence time and then by the density for each solid component. It is assumed that 80% of the inulin in the root feed can be removed in the reactor in an aqueous mixture of 35 wt% inulin. An inlet water stream sufficient enough to meet this is added to the reactor, and is assumed to be 70°C. The energy required to maintain this water temperature in the reactor and subsequent units is neglected for this simulation.

The dissolved air flotation tanks were both assumed to have a twenty-minute residence time. The first tank used a 30:1 water to solids volume ratio was assumed for the first tank, while a 10:1 ratio was used for the second tank. The volumes determined were used to cost the tanks as horizontal process vessels using relationships from Turton (2012).

The spray dryer was costed using correlations from Couper (2012) based on the mass per unit time of water being evaporated. The duty required to heat and evaporate the inlet liquid stream neglected the mass of the solids. The mass flow rate of water entering the dryer, the heat capacity of water, the heat of vaporization, and a temperature difference of 30°C was used to determine the required heat duty. The utility cost for dryer was equivalent to the cost of natural gas required to meet this heat duty.

The vibrating screens were both costed according to Turton (2012) correlations. Since no run data exists for this process, an average operating area was calculated for the larger of the two using the average integral of the applicable Turton (2012) equation, and the 0.6 power rule was used to size the smaller one.

For the second vibrating screen, the required amount compressed air was determined using a correlation from Crowl (2014), along with some assumptions about the positioning of the nozzles. This flow rate was input into a CHEMCAD simulation consisting of a feed stream, a rotary compressor, and a product stream, and from this, the required power was determined. This power was then used along with Turton (2012) correlations to cost both the compressor and its accompanying totally enclosed electric drive.

The vertical mixing vessel was given arbitrary dimensions that would satisfy mixing time requirements within an order of magnitude, determined using McCabe (2005) correlations. The vessel was costed using Turton (2012) correlations, using a pressure factor corresponding 304 stainless steel in atmospheric conditions.

The agitator was designed as an HE-3 impeller using McCabe (2005) correlations. Various assumptions had to be made about the physical properties of the natural rubber, since no run data exists for this process. Most notably, the viscosity was approximated using the log-mean of minimum and maximum rotating cylindrical viscometer readings from Holden (1965). The power required was then used along with Turton (2012) correlations in order to cost the agitator.

The dryer was modeled as an adiabatic drum dryer made of 304 stainless steel. The heat duty required was equal to the amount of energy needed to raise the mixture temperature, as well as the heat of vaporization of water. The heat transfer from the surface of the dryer was assumed to be dominated by conduction, and the overall heat transfer coefficient was determined accordingly. This was used along with the temperature driving force to find the required heat transfer area, which was then used along with Turton (2012) correlations to cost the dryer. Rather than computing the required amount of natural gas, a price per 1 million BTU was obtained from Henry Hub index March 2017 price, and was used along with the heat duty to assign a utility cost.

An attempt was made to obtain a quote for a rubber block former, but since the project is still in early phases of design, not enough information is available to make a reasonable estimate.

Economic Summary (Data and Results)

Greenhouse

Installed Cost

The installed cost of the greenhouse was determined using various methods. Many of the installed costs were determined by scaling up the costs of a smaller greenhouse that uses similar equipment or finding similar equipment online. The installed costs for other equipment was determined using the equations and heuristics in Turton (2012). Detailed information on how the installed costs was determined for each piece of equipment can be found in Appendix A.

The installed cost of the germination racks was determined based on the need for 130 racks and was scaling up from a smaller greenhouse using similar germination racks. The installed cost of the robotic arms was based off the need for three arms and an installed cost provided by Will Hemker (April 2017). The installed costs of the grow racks and the lighting for the grow racks were determined based on the need for 2,825,342 ft^2 of growing area and scaling up from a smaller greenhouse that uses similar racks. The cost of the collection machines was determined based on the cost of a scissor lifts that would be like the collection machines. The cost of the root cutting machines was based off the price of a sickle bar mower that would be like the root cutting machines needed for this process. The installed cost of a dryer was calculated based off the heat that would need to be supplied to dry the dandelion roots and then using Turton (2012) to determine the installed cost of a furnace. The cost of the storage tanks was determined using Turton (2012) based off the tanks needing the volume to be able to hold enough water to fill all the tanks in the grow racks. The installed costs of the pumps were determined using Turton (2012) and the need for the pumps to be able to supply enough water for the ebb and flood hydroponic system. The installed cost for the fans were calculated using Turton (2012) based of a flow of air that would provide the greenhouse with one air change per minute. The installed cost of the greenhouse structure was determined by using the approximate area of a greenhouse and a price per ft^2 provided by Wil Hemker (April 2016).

Table 6: Breakdown of the installed costs of the pilot plant greenhouse and where to find the details regarding the costing of each piece of equipment.

Installed Costs		
Equipment	**Appendix**	**Cost**
Germination Racks	A.1	$ 1,800,000
Robotic Arms	A.2	$ 243,000
Grow Racks	A.3	$ 35,000,000
Lighting	A.4	$ 19,000,000
Collection Machines	A.5	$ 88,000
Root Cutters	A.6	$ 30,000
Root Dryer	A.7	$ 1,670,000
Storage Tanks	A.8	$ 3,600,000
Pumps	A.9	$ 21,750,000
Fans	A.10	$ 6,260,000
Greenhouse Structure	A.11	$ 28,200,000
Total Installed Cost		**$ 117,641,000**

The total installed cost for a greenhouse supplying enough dried dandelion roots to produce 100 t/y of natural rubber was found to be around $118,000,000. Much of the install cost comes from the grow racks, lighting for the grow racks, and the cost of the greenhouse structure. This is due to the large grow area needed to produce enough dandelion roots for the pilot plant. Another major cost are the pumps needed to supply the water for the ebb and flood hydroponic system.

Operating Costs

The operating costs were determined in a variety of ways. The cost of the seeds was determined by the number of seeds that would be needed each year. The cost of the natural gas was determined based on how much would need to be burned to dry the dandelion roots. The cost of the electricity for the lighting and the harvesting equipment was determined by scaling up the price from a smaller greenhouse that uses similar equipment based on the area needed for growing. The price of the electricity for the pumps was determined by how much power the pumps needed to run the ebb and flood hydroponic system. The cost of the water was determined by how much water was needed to replace the water lost from the harvested dandelion roots. The cost of labor was determined by estimating the number of employees would be needed to run the automated greenhouse. Detailed information on how the operating costs were determined can be found in Appendix A.

Table 7: Breakdown of the operating costs of the pilot plant greenhouse and where to find the details regarding the costing of each expense.

Operating Costs		
Expense	**Appendix**	**Cost**
Seeds	A.12	$ 8,200
Natural Gas	A.13	$ 38,000
Electricity for Lighting	A.14	$ 1,300,000
Electricity for Pumps	A.15	$11,400,000
Water	A.16	$ 1,400,000
Labor	A.17	$ 732,000
Total Operating Costs		**$14,878,200**

The total operating costs for the greenhouse was determined to be around $15,000,000/year. Most of the cost come from the electricity needed by the lights in the grow racks and the electricity needed by the pumps to supply the water for the ebb and flood hydroponic system. There is also a large cost of water due to so much water being lost from the harvesting of the dandelion roots.

Greenhouses for 100 kt/y Large-Scale Plant

The cost of greenhouses for the 100 kt/y natural rubber large-scale plant would be the price of 1,000 pilot plant greenhouses. This is due to the significant footprint of a single greenhouse supplying the dandelion roots needed to produce 100 kt/y of natural rubber. The footprint of a greenhouse pilot plant is approximately 10 acres (4 hectares) and the approximate footprint of a large-scale greenhouse would need to be 10,000 acres (4,000 hectares). Therefore, the installed costs of the 1,000 greenhouses needed to supply the large-scale plant would be approximately $118,000,000,000 and the operating cost of the greenhouse would be approximately $15,000,000,000/year.

Extraction Plant

Installed Cost

The total installed cost for the equipment for a processing plant with a capacity to produce 100 t/y of natural rubber from dandelion is $811,000. For a 100 kt/y plant the total installed cost was estimated to be around $27,000,000. As can be seen in the Table 7, the major influences of the capital costs are the high shear reactor, the spray dryer, and the drum dryer. Details and assumptions used for determining the costs can be found in the indicated appendices.

Table 8: Installed costs of the equipment in both the pilot plant and the large-scale plant.

Installed Costs			
Equipment	**Appendix**	**Pilot Case Cost**	**Large Scale Cost**
Cone Crusher	B.2	$2,089	$345,025
Rod Mill	B.3	$56,222	$291,776
High-Shear Reactor	B.4	$335,945	$8,815,935
DAF Tank 1	B.5	$15,416	$1,156,868
DAF Tank 2	B.6	$11,456	$492,394
Spray Dryer	B.7	$197,777	$14,780,219
Vibrating Screen 1	B.8	$33,479	$71,317
Vibrating Screen 2	B.9	$33,479	$72,863
Mixer	B.10	$25,281	$302,594
Drum Dryer	B.11	$99,943	$606,452
Total Installed Cost		$811,087	$26,935,443

Operating Cost

The total operating cost was determined using a cost of manufacturing correlation that incorporated various expenses typical of manufacturing facilities built in the past (Turton, 2012). The utility cost was assumed to be comprised of the cost of electricity and the cost of natural gas required to run the processes. For the pilot plant, the annual operating labor was estimated to be $4,300,000/y and the utility cost was estimated to be $137,000/y, bringing the total cost of manufacturing to $12,188,000/y. Assumptions and correlations used for estimating utility, operating labor, waste treatment, and cost of manufacturing can be found in Appendices B12, B13, B14, and B15 respectively. A breakdown of the electricity and natural gas costs are found in Tables 8 and 9 respectively.

Table 9: Cost of electricity for the equipment in the pilot plant.

Unit	**Power (kW)**	**Annual Cost ($)**
Cone Crusher	20	$10,528
Rod Mills	100	$52,640
High Shear Reactor	120	$63,168
Compressor Drive	6.06	$3,190
Agitator	3.15	$1,658
Total		**$131,184**

Table 10: Cost of natural gas for the equipment in the pilot plant.

Unit	**Heat Duty (W)**	**Annual Cost ($)**
Spray Dryer	64823	$5,565.99
Drum Dryer	6513	$301.40
Total Natural Gas Cost		$5,867.39

For the large-scale plant, the annual operating labor was estimated to be $8,170,000 and the utility cost was estimated to be $7,022,000, bringing the cost of manufacturing to $54,469,000/y. The electricity and natural gas usage and costs are available in Tables 10 and 11.

Table 11: Cost of electricity for the equipment in the large-scale plant.

Unit	Power (kW)	Annual Cost ($)
Cone Crusher	137.5	$72,380
Rod Mills	953	$501,659
High Shear Reactor	1091	$574,302
Compressor Drive	46.66	$24,562
Agitator	25.21	$13,271
Total		**$1,186,174**

Table 12: Cost of natural gas for the equipment in the large-scale plant.

Unit	Heat Duty (W)	Annual Cost ($)
Spray Dryer	64460000	$5,535,200
Drum Dryer	3507716	$301,136
Total Natural Gas Cost		$5,836,335.93

Product Value

The main products considered from the separation stage of the process are natural rubber, inulin, and glucose. Natural rubber was valued at $2,367/tonne and glucose was valued at $398/tonne based on information available from Index Mundi (2017). Inulin was valued at $6,462/tonne by dividing the inulin global market by the estimated global production of inulin reported by Grand View Research (2015). Dandelion greens were valued at $20,723/tonne from wholesale values found in Pacific Botanicals Catalogue (2012). With these values it was determined that the pilot plant would annually produce $237,000 in natural rubber, $2,585,000 in inulin, $2,900,000 in dandelion greens, and $16,000 in glucose for a total of $5,800,000 in value of products. The large-scale plant would produce 1000 times these numbers, resulting in $5.8 billion in total value of products.

Discussion

For both the pilot and the large-scale plant, it can be concluded that based on the product value and the operating cost of the two processes that there is little economic feasibility for the design as presented. Even when neglecting capital costs, the annual operating costs for both processes totals to $27.2 million for the pilot scale 100 t/y process and $15 billion for the 100 kt/y scale process. This means that the pilot scale process would lose $21.4 million per year and that the large-scale process would lose $9.2 billion per year, ignoring annuity and capital costs.

The extraction process contributes roughly half (45%) of the pilot-scale cost, but a negligible amount (<1%) to the large-scale process. For both cases, the operating cost of the extraction process is much greater than the value of the products. Ignoring capital costs, the pilot plant could break even if the dried dandelion roots are valued at $27.19/kg, or if the total annual operating cost was $3.2 million (a reduction of 88%). For the large-scale plant, these values are

$15.05/kg of dandelion roots and $5.8 billion in annual operating costs (a reduction of 61%). For reference, the dried dandelion roots are currently valued at $5.80/kg. Based on this, the proposed large-scale design for the extraction process could prove adequate for future endeavors if the farming and harvesting of the dandelions was 160% more efficient.

One recommendation to decrease the costs of the greenhouse would be to confidently estimate a higher yield of rubber per dandelion root. This would significantly reduce the cost of the greenhouse due to the number of dandelion roots that need to be harvested is proportional to the yield of rubber per dandelion root and the size and cost of the greenhouse being proportional to the number of dandelion roots that need to be harvested. Therefore, if the rubber content of rubber in a dandelion root would go from 10% to 20% it would roughly cut both the installed and operating costs in half. Similar results would be observed if other assumptions, such as the weight of each dandelion root, could be improved. Without these assumptions being changed there is essentially no way of decreasing the size of the greenhouse (grow racks, lighting, and greenhouse structure).

Another recommendation to decrease the cost of the greenhouse would be to choose a different hydroponic method, such as aeroponics or deep-water culture. Choosing a different hydroponic method could significantly reduce the price of the pumps. Reducing the cost of the pumps would also decrease the operating cost of the pumps, which is the greatest operating cost right now. However, research would need to be done to see if similar root size and rubber content would change with different types of hydroponics. It would also be beneficial to determine if there is a way to recapture the water lost in the drying process to reduce the cost of water each year.

The last recommendation in regards to the greenhouse would be to abandon the idea of vertical farming. The costs of the racks, lighting, and ebb and flood hydroponic system needed for a vertical greenhouse are excessively expensive to make the greenhouse economically feasible. A possible replacement for the 3D greenhouse would be to use a semi-controlled 2D farming method. This would be a larger footprint; however, it would eliminate the need for the racks and the lighting. This new method would also allow for the use of hydroponics.

There are many areas where assumptions used for modeling the extraction process may be improved. Empirical data used for the solubility of inulin is not specific to inulin extracted from TKS Dandelion root. Experiments should be performed to identify exactly how much inulin can be extracted from roots at various residence times, water flows, water conditions (temperature and pH), and root orientations (grinding methods). Likewise, similar experiments should be performed in order to collect more relevant empirical data on the interaction of cellulase enzyme with the cellulose components of the dandelion root. This could lead to a better yield of glucose product and less cellulose waste. Identifying and improving assumptions will yield to more accurate predictions of the process model.

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Appendices

Appendix A: Costing the Greenhouse

Appendix A.1: Germination Racks

The installed costed of the germination racks are based off scaling up from the number of germination racks in a smaller greenhouse (Wil Hemker, April 2017) using the same type of germination racks.

Germination Racks for smaller greenhouse: 6 Racks = $83,200

Germination Racks for pilot plant greenhouse: 130 Racks = $1,800,000

Appendix A.2: Robotic Arms

The installed cost for the robotic arms was calculated based on a price from Wil Hemker (April 2017).

Install cost for a robotic arm = $81,000

It was estimated that there needs to be three robotic arms.

Total install cost = ($81,000/arm) (3 arms) = $243,000

Appendix A.3: Grow Racks

The installed cost of the grow racks was calculated by scaling up the installed costs of a smaller greenhouse (Wil Hemker, April 2017) based on the grow area needed for the dandelions. The smaller greenhouse uses similar grow racks to the racks used in the greenhouse for the pilot plant.

Grow Racks for smaller greenhouse: 107,520 ft^2 = $1,344,000

Grow Racks for pilot plant greenhouse: 2,835,342 ft^2 = $35,000,000

Appendix A.4: Lighting for Grow Racks

The installed cost of the lighting for the grow racks was calculated by scaling up the installed costs of the lights from a smaller greenhouse (Wil Hemker, April 2017) based on the area of the growing area.

Lighting for smaller greenhouse: 107,520 ft^2 = $733,120

Lighting for pilot plant greenhouse: 2,835,342 ft^2 = $19,000,000

Appendix A.5: Dandelion Collector

The installed cost of the collectors for the dandelions was based off scissor lifts that are like the collectors used in the process.

Cost for a scissor lift = $44,000 (http://www.cestools.com/genie-gs-2669-dc-self-propelled-elec-scissor-lift-32-ft-h-1500lb-cap/)

Number of scissor lift needed = 2

Total installed costs = $88,000

Appendix A.6: Dandelion Root Cutter

The installed cost for the dandelion root cutter was based off a sickle bar mower that is like the cutter that will be used in the process.

Cost of a sickle bar mower = $5,000

(http://www.beavervalleysupply.com/sectionc/enrossisbm.htm

Number of sickle bar mowers needed = 6

Total installed cost = $30,000

Appendix A.7: Dryer

The installed cost of the dryer was based off the installed cost of a furnace in Turton (2012). The dryer needs to remove 70 g of water from each dandelion to get the dandelion root from 80% water to 10% water.

Number of dandelion roots that need to be dried every 15 minutes = 1440 dandelion roots

Amount of water that needs to be removed = 0.336 kg water/sec

$$Energy\ Needed\ to\ heat\ water\ to\ 100C = \left(0.336\frac{kg}{sec}\right)\left(4.184\frac{kJ}{kg * C}\right)(75\ C) = 105\ kW$$

$$Energy\ needed\ to\ vaporize\ water = \left(0.336\frac{kg}{sec}\right)\left(2257\frac{kJ}{kg}\right) = 758\ kW$$

Total energy needed to heat and vaporize water (70% efficiency) = 1234 kW

Purchase cost (C_p^0) of furnace from Figure A.4 in Turton (2012) = \$494,000 (CEPCI = 397)

Purchase cost (C_p^0) in 2016 (CEPCI = 542) = \$674,000

Bare module cost from Turton (2012) = $C_p^0 F_{BM}$ = (\$674,000) (2.1) = \$1,400,000

Installed Cost = C_{BM}*1.18 = (\$1,400,000) (1.18) = \$1,670,000

Appendix A.8: Tanks

The installed costs of the tanks were based off the installed cost of a fixed roof tank in Turton (2012). There needs to be enough volume to be able to hold enough water to fill all the tanks.

Volume needed to fill all the tanks = 66,873 m^3

Due to the maximum size of 30,000 m^3/tank (Turton, 2012) there will need to be 3 23,000 m^3 tanks

Purchase cost (C_p^0) of a tank from figure A.7 in Turton (2012) = \$759,000 (CEPCI = 397)

Purchase cost (C_p^0) in 2016 (CEPCI = 542) = $1,036,000

Installed Cost = C_{BM}*1.18 = ($1,036,000) (1.18) = $1,200,000/tank

Total installed cost = ($1,200,000) (3 tanks) = $3,600,000

Appendix A.9: Pumps

The installed costs of the pumps were based off the installed cost of a centrifugal pump in Turton (2012). The pumps need to be able to supply a flow of 8,360 m^3/min to the tanks in the grow racks to ensure that each tank will be filled every once every eight minutes. The water will also need to be pumped to a maximum height of 30 feet.

The maximum flow rate for a centrifugal pump is 38 m^3/min (Turton, 2012), so there will need to 240 pumps pumping 35 m^3/min of water. This will make for 2 pumps for every column of tanks. Due to the water, always being pumped into the shallow end of the tanks, 120 of the pumps will only pump through approximately 100 feet of piping and 120 pumps will pump through approximately 800 feet of piping (to reach the other side of the grow racks).

To calculate the maximum power needed for each pump you need the ΔP and the flowrate for each pump.

Pressure to pump the water 30 feet high:

$$Pressure = \left(1000\ \frac{kg}{m^3}\right)\left(9.81\frac{m}{s^2}\right)(9.144\ m) = 89{,}703\ Pa = \ .897\ bar$$

The pressure drop through a pipe is estimated to be 2 psi/100 feet from Table 11.8 in Turton (2012).

Pressure drop for 100 feet = 0.138 bar

Pressure drop for 800 feet = 1.103 bar

Total pressure needed for the pumps with 100 feet of piping = 1.035 bar

Total pressure needed for the pumps with 800 feet of piping = 2.000 bar

Power needed (Table 11.9) (Turton, 2012) for pumps with 100 feet of piping (80% efficiency):

$$Power = \frac{(1.67)\left(35\ \frac{m^3}{min}\right)(1.035\ bar)}{0.8} = 75.25\ kW$$

Power needed (Turton Table 11.9) for pumps with 800 feet of piping (80% efficiency):

$$Power = \frac{(1.67)\left(35\ \frac{m^3}{min}\right)(2.000\ bar)}{0.8} = 145.43\ kW$$

Cost of Pumps with 100 feet of piping:

Purchase cost (C_p^0) of a pump from Figure A.3 (Turton, 2012) = \$11,300 (CEPCI = 397)

Purchase cost (C_p^0) in 2016 (CEPCI = 542) = \$15,400

Bare module cost (Turton, 2012) = $C_p^0F_{BM}$ = (\$15,400) (1.89+1.35*1.5) = \$60,300

Installed Cost = C_{BM}*1.18 = (\$60,300) (1.18) = \$71,200/pump

Cost of Pumps with 800 feet of piping:

Purchase cost (C_p^0) of a pump from Figure A.3 (Turton, 2012) = \$17,500 (CEPCI = 397)

Purchase cost (C_p^0) in 2016 (CEPCI = 542) = \$23,800

Bare module cost (Turton, 2012) = $C_p^0F_{BM}$ = (\$23,800) (1.89+1.35*1.5) = \$93,300

Installed Cost = C_{BM}*1.18 = (\$93,300) (1.18) = \$110,000/pump

Total installed cost of the pumps = \$21,750,000

Appendix A.10: Fans

The installed costs for the fans were calculated using Turton (2012). The fans need to have a high enough airflow to provide the greenhouse with one air change per minute.

Volume of the greenhouse = 16,800,000 ft^3 = 475,700 m^3

Required air flow = 475,700 m^3/min = 7930 m^3/sec

This will require 80 fans providing 100 m^3/sec (maximum airflow from Turton (2012)).

Purchase cost (C_p^0) of a fan from Figure A.3 (Turton, 2012) = \$18,000 (CEPCI = 397)

Purchase cost (C_p^0) in 2016 (CEPCI = 542) = \$24,600

Bare module cost (Turton, 2012) = $C_p^0 F_{BM}$ = (\$24,600) (2.7) = \$66,400

Installed Cost = C_{BM}*1.18 = (\$1,400,000) (1.18) = \$78,300/fan

Total Installed Cost = (\$78,300) (80 fans) = \$6,260,000

Appendix A.11: Greenhouse Structure

The installed cost of the greenhouse structure was based off a price per area given by Wil Hemker (April 2017).

Area of greenhouse structure = 480,000 ft^2

Price of greenhouse structure = \$60/ft^2

Installed cost = \$28,200,000

Appendix A.12: Seeds

The price of the seeds is based off the price of dandelion seeds found online.

Seeds needed per year = 12,500,000 seeds/year

Price of Seeds = \$500/lb (http://www.johnnyseeds.com/herbs/herbs-for-salad-mix/dandelion-seed-951.html)

Number of seeds per lb = 764800 seeds/lb

Need 16.34 lbs/year of seeds

Price of seeds = \$8,200/year

Appendix A.13: Natural Gas

The price of natural gas was costed based of the amount of energy the natural gas needs to provide to the furnace to dry the dandelion roots.

Water removed from roots = (0.07 kg/dandelion root) (50,000,000) = 3,500,000 kg water/year

$$Energy\ needed\ to\ heat\ water\ to\ 100C = \left(3{,}500{,}000\ \frac{kg}{year}\right)\left(4.184\frac{kJ}{kg * C}\right)(75\ C)$$

$$= 1{,}098{,}300{,}000\ \frac{kJ}{year}$$

$$Energy\ neded\ to\ vaporize\ water = \left(3{,}500{,}000\frac{kg}{year}\right)\left(2257\frac{kJ}{kg}\right) = 7{,}899{,}500{,}000\ \frac{kJ}{year}$$

Total energy needed to heat and vaporize water (70% Furnace Efficiency) = 12,854 GJ/year

Price of natural gas (Henry Hub Index, 2017) = \$2.98/GJ

Cost of Natural Gas = \$38,000/year

Appendix A.14: Electricity for Lighting and Harvesting Equipment

The cost for electricity for the lights and the harvesting equipment was calculated by scaling up a smaller greenhouse (Wil Hemker, April 2017) that uses the lights and similar harvesting equipment.

For smaller greenhouse: 107,520 ft^2 = \$50,000/year

For greenhouse for pilot plant: 2,835,342 ft^2 = \$1,300,000/year

Appendix A.15: Electricity for Pumps

The cost of the electricity needed for the pumps was calculated by the average power the pumps will use. To see how the power required by the pumps see Appendix A.10.

The maximum power needed for the 120 pumps with 100 feet of piping was calculated as 75 kW. The minimum power needed for a pump with 100 feet of piping is 10 kW. The average power for these pumps is 42.5 kW.

The maximum power needed for the 120 pumps with 800 feet of piping was calculated as 145 kW. The minimum power needed for a pump with 800 feet of piping is 80 kW. The average power for these pumps is 112.5 kW.

Total power for the 240 pumps = 18,600 kW

Total electric power per year = 162,936,000 kWh

Price of electricity for industrial processes = $0.07/kWh (Electric Power Monthly, 2017)

Total cost of electricity = $11,400,000/year

Appendix A.16: Water Costs

The cost of water was calculated based on the amount of water that will need to be added to make up for water that will be lost from the dandelion roots.

Water lost per dandelion root harvested = 72 g/root

Water lost per year from harvesting the dandelion roots = 3,600,000 kg/year

Volume of water lost per year = 951,000,000 gallons/year

Price of Water (https://www.fcwa.org/story_of_water/html/costs.htm) = $1.50/1000 gallons

Cost of water = $1,400,000/year

Appendix A.17: Labor Cost

The labor cost for operating the greenhouse was calculated by estimating the number of each type of worker would be needed to operate the greenhouse. Because the greenhouse is fully automated, the required number of workers is significantly less than a normal greenhouse of this size.

It was determined that there would need to be a supervisor, a quality control expert, and two maintenance workers at the greenhouse always. This means there will need to be four supervisors, four quality control personnel, and eight maintenance workers total. The average salary for a maintenance worker is around $37,000/year. The average salary for quality control personnel is around $51,000/year. The average salary for a plant supervisor is around $58,000/year.

Total cost of labor = $732,000/year

Appendix B. Process Design Calculations for the 100 kt/y Case

Appendix B.1 Useful Properties and Equations

Equation B1. CEPCI inflation considerations, from Turton (2012). C_1 is the cost when the index is I_1, and C_2 is the cost when the index is I_2. For reference, the 2016 CEPCI is 541.7 (Jenkins, 2017). This will be used to correct 2001 dollars to 2016 dollars.

$$C_2 = C_1\left(\frac{I_2}{I_1}\right) = C_1\left(\frac{541.7}{307}\right) = 1.7645C_1$$

Equation B2. Equipment bare-module cost from Turton (2012). Correlations for F_{BM}, B_1, B_2, F_M, and F_P can be found in the textbook appendix corresponding to the equation.

$$C_{BM} = C_p^o F_{BM} = C_p^o(B_1 + B_2 F_M F_P)$$

Equation B3. General form of the Turton (2012) purchased cost correlation, using values from table B2. The result is in 2001 US Dollars, with a CEPCI of 307.

$$C_p^o = 10^{K_1 + K_2 \log A + K_3 (\log A)^2}$$

Equation B4. The total module cost of each unit is determined using equation 7.12 from Turton (2012).

$$C_{TM} = 1.18C_{BM}$$

Table B1: Equipment purchased cost correlation factors from Turton (2012), for use with equation B3.

Equipment	Type	K_1	K_2	K_3	Capacity, A	Units	Min	Max
Agitator	Impeller	3.8511	0.7009	-0.0003	Power	kW	5	150
Compressor	Rotary	5.0355	-1.8002	0.8253	Fluid Power	kW	18	950
Compressor Drive	Electric--totally enclosed	1.956	1.7142	-0.2282	Shaft Power	kW	75	2600
Dryer	Drum	4.5472	0.2731	0.1340	Area	m2	0.5	50
Screen	Vibrating	4.0485	0.1118	0.3260	Area	m2	0.3	15
Vessel	Vertical	3.4974	0.4485	0.1074	Volume	m3	0.3	520
Vessel	Horizontal	3.5565	0.3776	0.0905	Volume	m3	0.1	628
Reactor	Mixer/Settler	4.7116	0.4479	0.0004	Volume	m3	0.04	60

Table B2: Physical properties used during calculations

Species	Density (kg/m^3)	Heat Capacity (J/kg-K)
Natural Rubber	920	1880
Water	1000	4180
Methane		2200
Inulin	1350	
Glucose	1500	

Appendix B. 2 Cone Crusher

The cone crusher is used to reduce the size of the dried roots from 200mm to 25mm. There is no change between the inlet and outlet mass flows. The power consumption was interpolated from tabulated data of capacity versus power consumption from Chemical Engineer's Handbook (1988). The install cost was estimated using the following correlation from Couper (2012).

$$C = 1.89W^{1.05}$$

Where C is the cost in K$ (US) before CEPCI adjustment and W is the capacity of the crusher in tons/hr. The cost would be adjusted using the CEPCI index using equation B1. The relevant values for the cone crushers in both cases are summarized in the following table:

Table B.3: Installed costs for the cone crusher for the pilot and large-scale plant.

Case	Capacity (tonne/hr)	Power (kW)	Cost
Pilot	1	20	$2,089
Large Scale	125	137.5	$345,025

Appendix B.3 Rod Mill

The rod mill is used to reduce the size of the roots crushed by the cone crusher further down to 2.5mm. There is no change between the inlet and outlet mass flows. The power consumption was interpolated from tabulated data of capacity versus power consumption from Chemical Engineer’s Handbook (1988). The install cost for each rod mill was estimated using the following correlation from Couper (2012):

$$C = 16.10W^{0.69}$$

Where C is the cost in k$ (US) before CEPCI adjustment and W is the capacity of the mill in tons/hr. For sizes that were outside the usable range for this correlation, multiple mills would be costed to meet the capacity. The cost is then adjusted using the CEPCI index using equation B1. The relevant values for the rod mills in both cases are summarized in the following table:

Table B4: Installed costs for the rod mill for the pilot and large-scale plant.

Case	Capacity (tonne/hr)	Quantity	Power (kW)	Cost
Pilot	1	1	100	$56,222
Large Scale	125	5	953	$291,776

Appendix B.4 High-Shear Reactor

The ground roots and a water stream of roughly 70°C is fed into the high-shear reactor. It is assumed that 80% of inulin from the dried roots could be dissolved and separated in a high-shear reactor based on previous work. It is assumed that the inulin will dissolve in water at a maximum mass fraction of 0.35 based on Phelps (1964). The reactor volume needs to be large enough to meet the 25:1 by volume ratio of water to dandelion root suggested by Wade (2011). A 30:1 ratio was used to allow for additional volume if needed and a residence time of 20 minutes was assumed for the reactor. The volume for the reactor in both cases was determined using the following relation:

$$Volume = \left(\frac{Liquid}{Solid} Ratio\right) * SolidVolumeFlow\ Rate * Residence\ Time$$

Where the V is the reactor volume. The solid volume flow rate is determined by dividing the inlet mass flow rate of each solid entering the reactor with its density from Table B2 and summing the volumes.

The reactor was costed for both cases as a carbon steel reactor operating at 0 barg using equations B1, B2, and B3 and values from Turton (2012). The relevant values for both cases are tabularized.

Table B5: Installed costs for the high-shear reactor for the pilot and large-scale plant.

Case	**Volume (m3)**	F_{BM}	C_{BM}
Pilot	0.84	4	$335,945
Large Scale	840	4	$7,471,131

Appendix B.5 Dissolved Air Flotation Tank 1

The first DAF tank has an inlet from the sheared roots from the high-shear reactor. A dosage of cellulase enzyme based on the recommendation from the patent by Wade (2011) is added to this tank continuously to help break down the cellulose component of the dried roots with a small benefit of producing a small amount of glucose. A recycle water stream flows into the tank from the second DAF tank downstream in addition to a fresh water stream to maintain a proper liquid level in the tank. It is assumed that the remaining inulin in the process stream is separated in this tank and is sent to a spray dryer to with the inulin stream from the reactor. It is assumed from the literature (Liu, 2015) that at this loading and temperature 10% of the cellulose will be converted to glucose. This stream is sent to the spray dryer.

Based on the recommendations from the patent by Wade (2011), a residence time of 20 minutes was assumed in the tank. A 25:1 volume ratio of water to solids was recommended. The volume of the tank was determined using the same method used for the high shear reactor. The DAF tank was costed as a carbon steel horizontal process vessel operating at 0 barg using equations B1, B2, and B3 and values from Turton (2012).

Table B6: Installed costs for the DAF tank 1 for the pilot and large-scale plant.

Case	**Volume (m3)**	**k1**	**k2**	**k3**	**B1**	**B2**	**C_{BM}**
Pilot	0.54	3.5565	0.3776	0.0905	1.49	1.52	$15,416
Large Scale	543	3.5565	0.3776	0.0905	1.49	1.52	$980,397

Appendix B.6 Dissolved Air Flotation Tank 2

The second DAF tank receives an inlet stream from DAF Tank 1. In this tank natural rubber coagulates and is separated from the cellulose to be further dried in the later stages. Water from this tank is recycled back to DAF Tank 1 while fresh water is continuously added to this tank. A 10:1 liquid to solid ratio is appropriate for this tank (Wade 2011) and a 20-minute residence time is assumed. The volume and install cost of the DAF tank is determined the same way as DAF Tank 1.

Table B7: Installed costs for the DAF tank 2 for the pilot and large-scale plant.

Case	Volume (m3)	k1	k2	k3	B1	B2	C_{BM}
Pilot	0.195	3.5565	0.3776	0.0905	1.49	1.52	$11,456
Large Scale	195	3.5565	0.3776	0.0905	1.49	1.52	$417,283

Appendix B.7 Spray Dryer

The inulin and glucose product streams are fed into a spray dryer. A narrow nozzle sprays the product thinly while air that is heated by burning natural gas evaporates the water. The mass of water that needs to be evaporated in the pilot case is 98 kg/hour and for the large-scale case is 98 tonne/hour. The required heat duty for both cases is determined using the following equation:

$$Q = \sum m C_p \Delta T + m \Delta H_{vap}^{H_2O}$$

Where Q is the required heat duty, m is the mass flow rate of the water entering the dryer, Cp is the heat capacity of the water, ΔT is the difference between the final and initial temperature, and ΔH_{vap}^{H2O} is the heat of vaporization of water. The values used for heat capacity and heat of vaporization are obtained from McCabe (2005). The energy required to heat the inulin and glucose components of the mixture are neglected. The Q for the pilot and large-scale cases are 64,839 W and 64,839,000 W, respectively.

The cost of the spray dryer was determined using the following correlation from Couper (2012):

$$\mathrm{C} = 1.218\mathrm{Fexp}(0.8403 + 0.8526(\ln\mathrm{X}) - 0.0229(\ln\mathrm{X})^2$$

Where C is the install cost of the spray dryer, X is the mass of water to be evaporated per unit time, and F is a material factor. The spray dryer was assumed to be made out of carbon steel. For cases where X was outside of the range the correlation proves accurate for, multiple dryers were costed to meet the capacity. The relevant values are tabularized:

Table B8: Installed costs for the spray dryer for the pilot and large-scale plant.

Case	Capacity (lb water/hr)	Quantity	Cost
Pilot	216	1	$197,777
Large Scale	3000	72	$14,780,219

Appendix B.8 Vibrating Screen 1

The first vibrating screen was assumed to reduce the water in the natural rubber to 50% of total weight. 10% of the water coming out of the bottom is recycled, and the rest is purged. The mass balance can be found below.

Table B9: Vibrating screen 1 mass balance

	Inlet		**Outlet**		**Recycle**		**Purge**	
Species	**kg/h**	**m3/h**	**kg/h**	**m3/h**	**kg/h**	**m3/h**	**kg/h**	**m3/h**
Natural Rubber	12500	13.59	12500	13.59	0	0.00	0	0.00
Water	25957	25.96	12500	12.50	1495	1.50	14952	14.95
Total	38457	39.54	25000	26.09	1495	1.50	14952	14.95

The screen size was approximated by taking an average integral of equations B1 through B3 with table B1 factors for a vibrating screen, as seen below.

$$\overline{C_{BM}} = 1.7645 \frac{F_{BM}}{x_{max} - x_{min}} \int_{x_{min}}^{x_{max}} C_p^o \, dx$$

$$= 1.7645 \frac{1.34}{15 - 0.3} \int_{0.3}^{15} 10^{4.0485+0.1118\, log\, A+0.3260\, (log\, A)^2} \, dA$$

$$= \$60438$$

This number was used along with a numerical solver to find the corresponding area, 7.798 m^2.

Appendix **B.9** Vibrating Screen 2

The second vibrating screen was assumed to reduce the water in the natural rubber to 30% of total weight. All of the water coming out of the bottom is purged. The mass balance can be found below.

Table B10: Vibrating Screen 2 mass balance

	Inlet		**Outlet**		**Nozzles**		**Purge**	
Species	**kg/h**	**m3/h**	**kg/h**	**m3/h**	**kg/h**	**m3/h**	**kg/h**	**m3/h**
Natural Rubber	12500	13.59	12500	13.59	0	0.00	0	0.00
Water	12500	12.50	5357	5.36	0	0.00	7143	7.14
Compressed Air	0	0.00	0	0.00	1782	766.46	0	0.00
Total	25000	26.09	17857	18.94	0	0.00	7143	7.14

The operating area was determined using a 0.6 power rule, as follows.

$$A = A_0 \left(\frac{\dot{m}_{in}}{\dot{m}_{0,in}} \right)^{0.6}$$

$$= (7.798\, m^2) \left(\frac{25000 \frac{kg}{h}}{38457 \frac{kg}{h}} \right)^{0.6}$$

$$= 6.022\, m^2$$

Using equations B1 through B3 and table B1 for a vibrating screen, the cost of the second screen was determined to be $C_{BM} = \$51004$.

The compressed air passed over screen 2 was chosen to have a pressure of 2 bar, and the mass flowrate was determined using equation 4-7 from Crowl (2014), for air leaking from a well-rounded 0.25” diameter nozzle. The density of air was calculated using the ideal gas law at 298 K.

$$Q_m = AC_0\sqrt{2\rho g_c P_g} = AC_0\sqrt{2\left(\frac{PM}{RT}\right)g_c(P-P_{atm})}$$

$$= \left(\frac{\pi(0.000635\ m)^2}{4}\right)(1)\sqrt{2\left(\frac{(200000\ Pa)\left(0.029\frac{kg}{mol}\right)}{\left(8.314\frac{J}{mol\cdot K}\right)(298\ K)}\right)\left(1\frac{m\cdot kg}{N\cdot s^2}\right)((200000-101325)\ Pa)}$$

$$= 77.49\frac{kg}{h}\ per\ nozzle$$

The vibrating screen is assumed to have a 3:1 rectangular geometry of 1.417m×4.250m.

$$A = xy = (x)(3x) \rightarrow x = 1.417\ m, y = 4.250\ m$$

There needed to be enough nozzles to cover the width of the screen, and assuming the nozzles spray in a cone developing into a circle of 10x the nozzle diameter, 23 nozzles will be required. The total mass flow of air required is 1782 kg/h.

$$\frac{1.417\ m}{(10)(0.00635\ m)} = 22.31 \approx 23\ nozzles \rightarrow (23\ nozzles)\left(77.49\frac{kg}{h}\ per\ nozzle\right) = 1782\frac{kg}{h}$$

This flowrate was used to simulate a simple 70% efficient compressor with a feed and product stream in CHEMCAD. The power required was found to be 46.44 kW. The compressor was sized using equations B1 through B3 with table B1 factors for a stainless steel rotary compressor.

$$C_{BM} = 1.7645C_{BM,1} = 1.7645C_p^oF_{BM}$$

$$= (1.7645)\left(10^{5.0355-1.8002\log 46.44+0.8253(\log 46.44)^2}\right)(5)$$

$$= \$187702$$

The compressor drive was also sized using this power, using equations B1 through B3 and table B1 factors for an electric, totally enclosed drive.

$$\begin{aligned} C_{BM} &= 1.7645C_{BM,1} = 1.7645C_p^o F_{BM} \\ &= (1.7645)\left(10^{1.9560+1.7142\log 46.44-0.2282(\log 46.44)^2}\right)(1.5) \\ &= \$61748 \end{aligned}$$

<u>Appendix B.10 Mixer</u>

The mixer was sized using correlations in chapter 9 of McCabe (2005). The mixing vessel was chosen to have a diameter of 2 m, a height of 5 m, and a content height of 3 m, yielding a volume of 15.71 m^3. The agitator was chosen to be an HE-3 impeller, giving it a diameter of 0.9 m, 0.45 times that of the tank (McCabe, 2005). The mixer was set to operate at 20 rpm in order to produce a low Reynolds number, as required by the chosen correlation.

$$Re = \frac{nD_a^2\rho}{\mu} = \frac{\left(\dfrac{20\,rpm}{60\,\dfrac{s}{min}}\right)(0.9\,m)^2\left(920\,\dfrac{kg}{m^3}\right)}{7238\,Pa\cdot s} = 3.43\times 10^{-2}$$

Since no run data or molecular weight distribution was available, the dynamic viscosity of the 30% wet natural rubber was assumed to be the log-mean of the minimum and maximum values from the cylindrical viscometer readings from Holden (1965), giving a value of 7238 Pa-s.

$$\mu_{avg} \approx \frac{10^4 - 10^{-2}}{\ln 10^4 - \ln 10^{-2}} = 723.8\,P = 7238\,Pa\cdot s$$

This mixture was assumed to behave similarly to a viscous liquid, allowing McCabe (2005) equation 9.20 to apply.

The mixing time was checked to ensure it had the capacity to reasonably mix the natural rubber. This was done using McCabe (2005) equation 9.32.

$$nt_T = 16.9\left(\frac{D_t}{D_a}\right)^{1.67}\left(\frac{H_{content}}{D_t}\right)^{0.5} \to t_T = 3.93\,min$$

This leaves more than enough time for the volume to be mixed to meet the specified flow rate.

The costing parameter for the impeller is the shaft power required for it to turn. This was found using McCabe equation 9.20, along with table 9.2 for K_L values.

$$P = K_L n^2 D_a^3 \mu = (43)\left(\frac{20\ rpm}{60\frac{s}{min}}\right)(0.9\ m)^3(7238\ Pa \cdot s) = 25.21\ kW$$

The mixing vessel was costed using equations B1 through B3 and table B1 factors for a vertical vessel made of stainless steel operating at 0 barg.

$$C_{BM} = 1.7645 C_{BM,1} = 1.7645 C_p^o (B_1 + B_2 F_P F_M)$$

$$= (1.7645)\left(10^{3.4974+0.4485\log 15.71+0.1074(\log 15.71)^2}\right)$$

$$\times\left((2.25) + (1.82)(3.2)\left(\frac{\frac{(0+1)(2)}{2[850-0.6(0+1)]} + 0.00315}{0.0063}\right)\right)$$

$$= \$90713$$

The agitator was costed using equations B1 through B3 and table B1 factors for an impeller mixer.

$$C_{BM} = 1.7645 C_{BM,1} = 1.7645 C_p^o F_{BM}$$

$$= (1.7645)\left(10^{3.8511+0.7009\log 25.21-0.0003(\log 25.21)^2}\right)(1.38)$$

$$= \$165723$$

Appendix B.11 Drum Dryer

The dryer was designed as an adiabatic drum dryer made of 304 stainless steel with 0.5” thick walls. The mass balance can be found in the table below.

Table B11: Dryer mass balance.

	Inlet		Outlet		Evaporation
Species	**kg/h**	**m3/h**	**kg/h**	**m3/h**	**kg/h**
Rubber	12500	13.59	12500	13.59	0
Water	5357	5.36	1389	1.39	3968
Total	17857	18.94	13889	14.98	3968

The dryer heats the mixture up to 100°C to evaporate the water until 10% by weight remains. The required heat duty was thus calculated to be the combination of these two heat flows.

$$Q = \sum m C_p \Delta T + \Delta H_{vap}^{H_2O}$$

$$= \left(\left(12500\,\frac{kg}{h}\right)\left(1880\,\frac{J}{kg\cdot K}\right) + \left(5357\,\frac{kg}{h}\right)\left(4180\,\frac{J}{kg\cdot K}\right)\right)$$

$$+ \left(3968\,\frac{kg}{h}\right)\left(2257000\,\frac{J}{kg\cdot K}\right)$$

$$= 3507716\,W$$

This heat duty was then set equal to the heat exchanger design equation for a temperature difference of 100°C between the wall and contents. The heat transfer was assumed to be dominated by conduction, thus making the overall heat transfer coefficient a function of the wall thickness and conductive heat transfer coefficient of steel. The heat transfer was assumed to be 70% efficient to account for any film developing on the surface of the dryer.

$$U = 0.70 \times \frac{1}{\frac{x_m}{k}} = \frac{0.70}{\frac{0.0127\,m}{20\,\frac{W}{m\cdot K}}} = 1102\,\frac{W}{m^2\cdot K}$$

Since the dryer is adiabatic, this heat duty could be set equal to that required for evaporation, and the required heat transfer area was found.

$$Q = \sum m C_p \Delta T + \Delta H_{vap}^{H_2O} = UA\Delta T$$

$$\rightarrow A = \frac{Q}{U\Delta T} = \frac{3507716\,W}{\left(1102\,\frac{W}{m^2 \cdot K}\right)((200\,K - 100\,K)} = 31.82\,m^2$$

This heat transfer area was then used with equations B1 through B3 and table B1 factors for a drum dryer to find the bare-module cost.

$$C_{BM} = 1.7645 C_{BM,1} = 1.7645 C_p^o F_{BM}$$

$$= (1.7645)\left(10^{4.5472+0.2731\log 31.82+0.1340(\log 31.82)^2}\right)(1.6)$$

$$= \$513942$$

Appendix B.12 Utility Costs

The utility costs considered for the processing step included the electricity required to run the cone crusher, rod mills, high shear reactor, compressor drives, and agitator in addition to the natural gas required to heat the dryers.

The electricity costs for the cone crusher, rod mills, high shear reactor, compressor drive and the agitator were determined using the EIA (2017, March 24) Ohio industrial average electricity price for January 2017 of \$0.0658/kW-h. An 8000-hour operating year was used.

$$Power\ (kW) \times \frac{\$0.0658}{kW \cdot h} \times 8000\ h = UtilityCost\ (\$/y)$$

For the dryer, the price of natural gas per 1 million BTU was obtained from Henry Hub index for April 2017 (EIA, 2017, April 19). This was used along with the required heat duty to find the utility cost. An 8000-hour operating year was used.

$$Heat\ Duty\ W = \left(\frac{1}{0{,}293}\right)\frac{MBTU}{h} \times \frac{\$3.145}{MBTU} \times 8000\ \frac{h}{y} = Annual\ Cost\ (\$/y)$$

Appendix B.13 Operating Labor

The number of operators needed was determined using equation 8.3 of Turton (2012) for thirteen pieces of equipment, eight of which involve solids handling.

$$N_{OL} = \left(6.29 + 31.7P^2 + 0.23N_{np}\right)^{0.5} = \left(6.29 + 31.7(8)^2 + 0.23(5)\right)^{0.5} = 45.12$$

$$\approx 46\ operators\ per\ shift$$

The cost of operating labor was found using the average 2017 salary for a grain-milling operator from the Bureau of Labor Statistics.

$$C_{OL} = 4.5 \times Nol \times \$39480/y = Anuual\ Labor\ Cost\ (\$/y)$$

Appendix B.14 Waste Treatment Costs

The cost of waste treatment was estimated using costs of \$36/tonne for solid waste and \$56/1000m^3 for tertiary water treatment from Turton (2012). For the pilot-scale plant, a total of 45 kg of cellulose waste and 68.6 kg of wastewater are produced per hour.

$$\left(\left(\frac{\$36}{tonne}\right)\left(45\frac{kg}{h}\right)\left(\frac{1\ tonne}{1000\ kg}\right) + \left(\frac{\$56}{1000\ m^3}\right)(68.6\ kg)\left(\frac{1\ m^3}{1000\ kg}\right)\right)\left(\frac{1\ y}{8000\ h}\right) = \$43695/y$$

For the large-scale plant, a total of 45 tonnes of cellulose waste and 68.6 tonnes of wastewater are produced per hour. Assuming an 8000 operating year, the total cost comes to \$12,990,735 per year.

Appendix B.15 Cost of Manufacturing

The cost of manufacturing (COM) was estimated using equation 8.1 in Turton (2012), assuming that the cost of raw materials is zero, because the dandelion roots are a part of this process. For the pilot-plant this cost is \$12,118,423 per year, and for the large-scale plant it is \$54,468,759. The calculation steps for the pilot-scale plant are shown below.

$$\begin{aligned} COM &= 0.280FCI + 2.73C_{OL} + 1.23(C_{UT} + C_{WT} + C_{RM}) \\ &= 0.280(\$811087) + 2.73(\$4300000) + 1.23\big((\$137051) + (\$43596) + (\$0)\big) \\ &= \$12{,}188{,}423/y \end{aligned}$$