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Bioplastic made from Kiwi Branches

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Abstract

The main goal of this work was to develop a product whose cellulose is extracted from kiwi branches. The product presented, Kiwiplast consists of a bioplastic film for food packaging. This way, it intends to create a circular economy and lower environmental impact. The extraction and production process were studied and scaled up to industrial level. The company would be located in Agueda, with a working force of 10 workers. An economic analysis has shown that this project requires an investment of 896 k€ and is viable and profitable.

1. Introduction

There are many agricultural products that are harvested each year, which leads to huge waste generation. Namely, the kiwi fruit had a yearly production of approximately 4.54 million tonnes in 2022, of which 45.67 tonnes were from Portugal (Shahbandeh 2024; Instituto Nacional de Estatística 2021). It is estimated that this production generates about 20% of waste, which includes leaves, stems, peels, roots, and flowers. All this waste is usually burned, which impacts not only the economy but also the environment. Using waste to extract compounds can allow the development of new products, which have been largely studied to lower economic losses while creating a circular economy system and meeting the population's needs simultaneously.

Another environmental problem the world's been facing in recent years is the pollution generated by the high quantities of plastic. More than 8 million tonnes of plastic go into the ocean every year, and this value is expected to double in the next two decades (Fava, 2022 17). If humanity does not rethink the way it produces and uses plastics, there will be more plastic than fish in the oceans by 2050 (MacArthur 2017). Kiwiplast intends to produce bioplastics for food packaging using cellulose extracted from the kiwi branches, in Portugal.

This work aims to discuss the whole process of designing a new chemical product. Characterization of the raw material, extraction of cellulose, manufacturing process and economic study of bioplastics are described in this article, leading to a circular economy and a less harmful product to the planet.

Kiwifruit is a worldwide appreciated fruit due to its chemical composition, flavor and antioxidant and anti-inflammatory properties. The kiwi plant is pruned twice a year and most of the kiwi production in Portugal is in the North and Central regions (Instituto Nacional de Estatística 2021). Globally, Portugal ranks in the top 10 kiwifruit producers, being fourth in Europe after Italy, Greece, and France (Shahbandeh 2024).

It was assumed that the company would be processing approximately 30% of the national waste generated, expecting to obtain 3,000 tonnes of kiwi branches each year. Kiwi branches are made up of 53% of water; this means the total dry weight of Kiwi branches is 1,410 tonnes per year (Manzone, Gioelli, and Balsari 2017).

The main components of kiwi branches are cellulose, hemicellulose, lignin, phenolic acids, flavonols and flavonoids (Silva et al. 2021). Cellulose and lignin are structural polymers with biorefining potential, while the rest of the components are aromatics with antioxidant, anti-ageing, anti-inflammatory and antibacterial properties. Cellulose is tasteless, odorless, has low solubility in water and in most organic solvents is also biodegradable. On the other hand, lignin has a strong hydrophobicity and solubility in hot alkali and is easily oxidizable.

Zespri, in cooperation with SCION, transformed kiwifruit waste into bioplastic materials such as spoons and knives for eating kiwi. VALORNATURE is a Interreg Project that aims to produce polypropylene reinforced with kiwi fibre, which is designed for injection moulding applications (Markotsis 2010).

2. Chemical Product Design

The methodology applied in the product design consisted of the following: ideas were selected based on what is reasonable to be done with the compounds present in our raw material. The ones that are present in low amounts are hard to extract and would make the manufacturing more expensive or complex. The product ideas that aligned the most with the market needs were selected and processes with some know-how in the industry were prioritized so that the upscale could be done more easily and have more favorable odds of being successful.

2.1. Needs and Ideas

The following needs must be fulfilled for our product to be successful. Decided needs are shown in Table 1.

Essential	Desirable	Useful
Active ingredients present in Portuguese kiwi branches	Sustainable extraction	Inexpensive
Manufactured in Portugal	Sustainable production	Easy logistics
	Biodegradable	B2B

Table 1: General needs.

Based on these needs, a brainstorming of ideas was done and divided into groups based on active compound from kiwifruit, Table 2.

Cellulose/Ph. Acids	**Ph. Acids/Flavanols**	**Sugars**	**Linalol/Ph.Acids**
Green cellphone cover	Toothpaste	Bioethanol	Antioxidant perfume
Cellulose hairbrush	Mouthwash		
Green bracelet	Antioxidant cream		
Quench blanket	Antioxidant pill		
Cellulose shoes	Sunscreen	**Actinidin**	**Naringin**
Glitter		Meat tenderizer	Sweetener
Bulletproof vest			
Wood coating			
Bioplastics for packaging	**Lignin**		
Fire retardant	Carbon fiber insulator		**Citric Acid**
Bactericide tissues	Phenolic resins		Food preserver
Disposable tableware			
Biochar Adsorbent			

Table 2: Product ideas divided based on active ingredients.

The selection matrix was prepared for the top 10 ideas to decide which would be the final product, as shown in Table 3. The subsequent 7 parameters with weight factors are shown in brackets:

-Sustainability (0.2) – Final product is more sustainable than already existing products and is less harmful to the environment;

-Innovation (0.1) – How revolutionary/new the product is;

-Active Ingredient Quantity (0.15) – How high is the composition of our raw material in the final product;

-Cost (0.2) - Expenses related to production;

-Ease of Regulation (0.1) – How difficult is to get licenses for our product to enter the market;

-Scientific Knowledge (0.1) – Already existing scientific knowledge about the product;

-Market Appeal (0.15) - Current and estimated product demand with respect to other products.

	Sustainability (0.2)	**Innovation (0.1)**	**Active Ingredient Quantity (0.15)**	**Cost (0.2)**	**Ease of Regulation (0.1)**	**Scientific Knowledge (0.1)**	**Market Appeal (0.15)**	**Total**
Fire Retardant	8	6	9	5	6	6	7	**6.8**
Bactericide Tissues	7	7	8	6	4	5	8	**6.6**
Carbon Fiber Insulator	6	8	9	3	8	6.5	7	**6.45**
Sweetener	7	5	5	4	2	9	7	**4.7**
Bulletproof Vest	6	10	9	3	4	4	3	**5.4**
Wood Coating	7	5	8	4	7	7.5	7	**6.4**
Biochar Adsorbent	7	7	10	8	4	5	8	**7.3**
Bioplastics	9	6	9	7	7	9	10	**8.25**
Food Preserver	7	4	6	5	2	6	6	**4.65**
Bioethanol	6	2	9	8	9	9	5	**6.9**

Table 3: Selection matrix.

The three best-ranked product ideas were Bioplastics for packaging, Biochar adsorbent and Bioethanol. Their needs are shown in Table 4.

	Essential	**Desirable**	**Useful**
Bioplastics for packaging	Easily recycled/reusable Safe to use same properties as synthetically produced product	Biodegradable short delivery routes between purchasing and manufacturing	Inexpensive Stable characteristics
Biochar adsorbent	Low-cost production High adsorption rates (fast kinetics)	High adsorption capacity High surface area (porous, small particles)	Ease of regeneration Ease of reuse
Bioethanol	Sustainable production High purity needed for fuel standards	Yield comparable to other waste material processing	Cheap processing Ease scale-up methods

Table 4: Selection matrix.

It was decided to choose Bioplastic for packaging since it scored the highest in our selection matrix. There can also be seen the potential for future growth of the bioplastics market to replace current plastics, which are harmful to the environment.

3. Manufacture

3.1. Product Specifications

Kiwiplast is a biodegradable general-purpose food packaging plastic film made of cellulose fibers from the pruning residues of kiwi crops around northern Portugal. The product is to be available in only one standard size, comprised of 25 µm thick machine-stretched film rolls of 48 kg, with a roll width of 1.5 meters. Kiwiplast rolls are designed for packaged organic goods at industry facilities and store displays, where load carrying is not required.

The matrix comprises 75% of the plastic and is composed of treated cellulose fibers and commercial cassava starch on a 3:1 ratio, which combined form a moderately resistant transparent composite by means of an outside plasticizer substance. For this role, high-purity glycerol is used at 37.5% w/w to the overall mixture (Cifriadi et al. 2017). Additionally, carvacrol is used in the composition (5% w/w) to attach to the plastic surface antibacterial properties necessary to the standards of food packaging applications (Luzi et al. 2017). Kiwiplast's main properties are available in Table 5.

Density ($g{\cdot}cm^{-3}$)	**Tensile Modulus** (MPa)	**Melting Temperature** (°C)	**Oxygen Permeability at 25 °C** ($g{\cdot}\mu m\ Day^{-1}\ m^{-1}\ mmHg^{-1}$)	**% Moisture Content** (5 weeks)	**Bacterial Growth** (CFU·ml-1)
1.98	**15**	**240**	**0.42**	**6.4**	**1.99x105**

Table 5: *Kiwiplast*'s film properties (Rahman et al. 2022; Shlush and Davidovich-Pinhas 2022; Yaradoddi et al. 2020; Azmin and Nor 2020; Luzi et al. 2017).

All the parameters above are in accordance with Regulation (EC) No 1935/2004 of the European Parliament and of the Council of 27 October 2004 on materials and articles intended to come into contact with food (Parliament 2004).

3.2. Manufacturing Process

Figures 3 and 4 show the flowchart of Kiwiplast's bioplastic production process. The former shows the extraction process of cellulose fibers, comprising 38.38% of the kiwi branches, while the latter describes the usage of this pulp in the actual process of making the film roll in a blown film extruder(Nemli et al. 2003). A chemical recovery system, also shown in Figure 3, is used to avoid uneconomical and environmentally hazardous waste of pulp reagents. By doing this, the plant can operate with basic water treatment facilities whose presence has been omitted in this work. Additionally, the amount of each reagent necessary is showcased in Table 6.

Reagent	**Weight percentage**	**Quantity (tonnes)**
NaOH	12.01	301.2
Na_2S	5.56	139.3
Na_2CO_3	2.93	73.5
NaOCl	3.63	90.9
$C_3H_8O_3$	5.42	136
Carvacrol	1.05	26.4
Starch	3.68	92.3
$Ca(OH)_2$	0.04	0.94
$CaCO_3$	65.64	1,646
Oil	0.04	1

Table 6: Semestral quantity of each reagent.

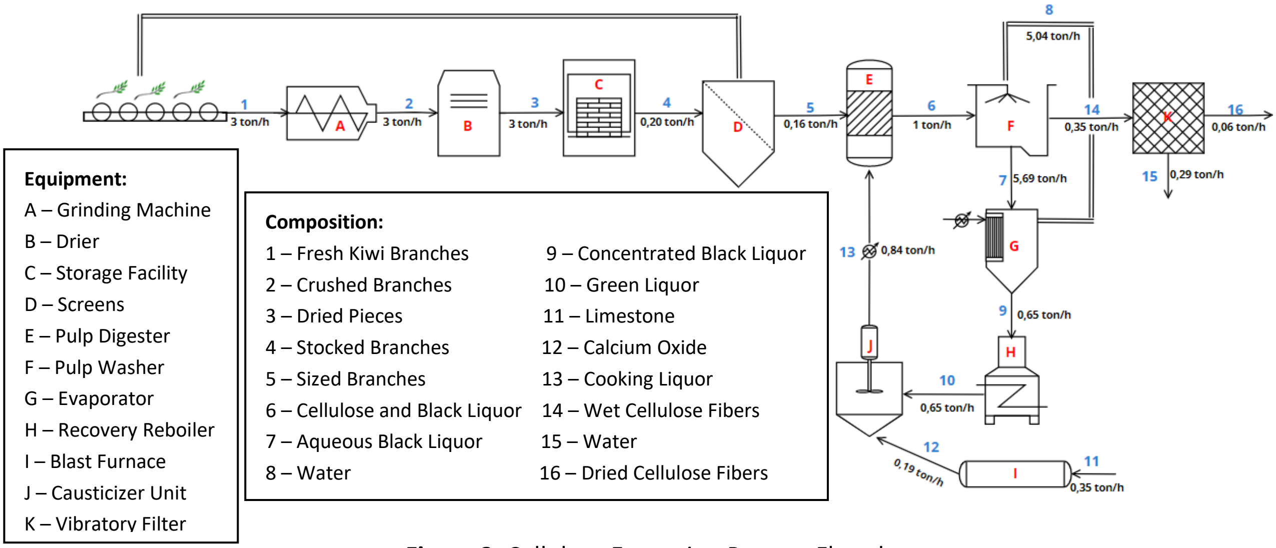

Figure 3: Cellulose Extraction Process Flowchart.

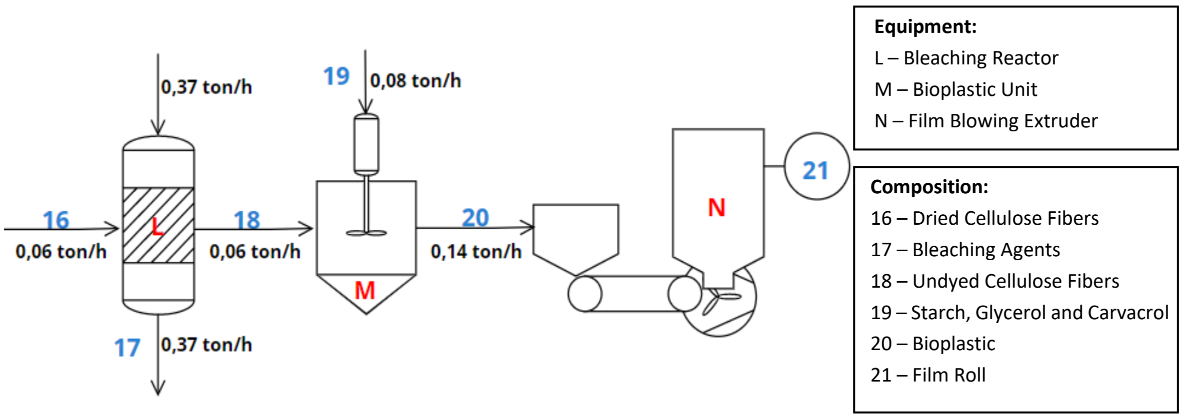

Figure 4: Bioplastic Film Process Flowchart.

The kiwi branches can be collected during pruning seasons, which take place at the end of spring and fall. The company pretends to work together with farmers located in Northern and Central Portugal, which accounts for almost all national production. Since this production is big enough for a good product output, and the company is situated in this area, no extra costs with import tax and long-distance transportation would be necessary. After proper establishment and negotiation, roughly 1500 tonnes are expected to be received per semester, arriving fresh at the company by means of a truck transport system. It is not expected to receive the full output of residues mentioned before as a part of these are already used by producers for other means, such as soil regeneration and household fuel. Seeing as the operation runs continuously, the branches' conservation process is required to be used until the next shipment arrives.

Thus, according to the flowchart in Figure 3, the first step of the process is to shred the branches into very small fragments in a grinding machine (A) that would operate with max capacity (3 ton/h) for 14 days, to prepare all the raw material as quickly as possible. The material is then dried (B), screened for appropriate sizing and stored under vacuum (C) in appropriate bags for further utilization. The drying step (B) would take about 9 days to conclude, and this number was achieved with an enthalpy calculation. Using the specific heat of wood as an approximation for the specific heat of the branches and using the specific heat of water, it was possible to calculate the amount of energy necessary to raise the temperature of the branches to 373 K, it was assumed that the dryer would operate at room temperature and use the heat of vaporization of water at that pressure to calculate the amount of heat used in vaporizing the water. Combining all the energy necessary– by raising the temperature of the branches and vaporizing the water, the net energy necessary for that process is calculated. Given the power and thermal efficiency of the dryer, it is possible to approximate the operating time for the process, which was approximately 9 days. These calculations are susceptible to errors, but the real value would not be very different, and the logistics of the drying process are still reasonable. The extraction process of cellulose fibers would be carried out by means of a wood digester (D). The flowrate for this step is 0.20 ton/h. The flowrate inside the digester was calculated using as a basis the volume of the digesting tank and the residence time; all the other flowrates were calculated so that this amount of material flowing is successfully processed. In this unit, the stored fragments enter an isothermal column reactor and are put into contact with reutilized hot cooking liquor (13) at 170 °C for a residence time of approximately 1.5 h (Shreve and Brink 1977). The cooking liquor's role is to remove lignin from the organic material since it inhibits further processing. It is composed of a 12.5% w/w aqueous solution of sodium hydroxide that removes the lignin from the cellulose fibers, sodium sulfide, which acts as the catalyst, and sodium carbonate, a stabilizer. The mixing of these reagents would be done in the same proportion used by softwood pulp factories (58.5% NaOH; 27% Na_2S; 14.5% Na_2CO_3) (Shreve and Brink 1977).

At the exit of the digester, a solution containing the lignin and used reagents (black liquor) is isolated from the cellulose fibers through a washing step with saturated liquid water. This diluted black liquor follows a chemical recovery system meant to retrieve the cooking liquor and burn the lignin and other organic materials present. Given the large quantities used in the process, this stage is crucial to avoid expenses with chemical reagents and their disposal.

The next phase of the process, shown in Figure 4, is the effective production of bioplastic film, where the soaked fibers are filtered (K) and amount to a total mass flow of 60 kg/h. The discrepancy of this number compared to the original 200 kg/h that would enter the reactor is related both to the lignin loss and the reaction efficiency inside the digester, which were assumed to be 80% of the original mass balance predicted in pulp factories (Shreve and Brink 1977). After this step, the fibers would be bleached by an aqueous solution of sodium hypochlorite (17) to make the plastic transparent, and they would be added to a mixing tank (M) together with the other constituents in the proportions and conditions explained previously. The resultant plastic material would be let to cool down by ambient air and would therefore be ready to be converted into the packaging mold. This would be done by means of a Film Blowing Extruder (N), which adjusts it to the size of the final product (21) and operates at a capacity of 140 kg/h, meaning that 1,101.9 tonnes of the final product would be produced annually. The last step consists of packaging and labelling the product.

During the whole process, a conveyor belt would also be used to transport the branches to the shredding machine, along with appropriate piping and pumps for the reagents and plastic, which have been disregarded in the process flow diagram and economic analysis. Additionally, oil would be electrically heated to be used for transferring the heat inside the heat exchangers inside the evaporator and cooking liquor reentrance at the digester.

4. Economic analysis

After the development of the product, it was necessary to perform an economic analysis in order to assess the viability of this project. A financial study was carried out, considering the various investments and costs, as well as the income associated with the product sales, for a period of 5 years.

4.1. Gantt diagram

The Gantt diagram is a time planning tool and, in many project management organizations, an important tool for planning and controlling projects and developments. It visualizes a sequence of activities on a time axis. These activities are displayed in the Gantt diagram, including name, start date, duration and end date and can also overlap in time. A more intensive phase of the activity is represented by a darker color. This makes it easy to check processing statuses and degrees of completion. In addition, the diagram provides support for resource planning, effort planning, cost planning and time recording.

The diagram is divided into the four phases of the chemical product development (CPD) process. These phases are needs, ideas, selection, and manufacturing. In this work, the activities are represented by marketing, research and development, investment, engineering, production and distribution. The Gantt chart represents these activities over a four-year period with four trimesters per year, Figure 5.

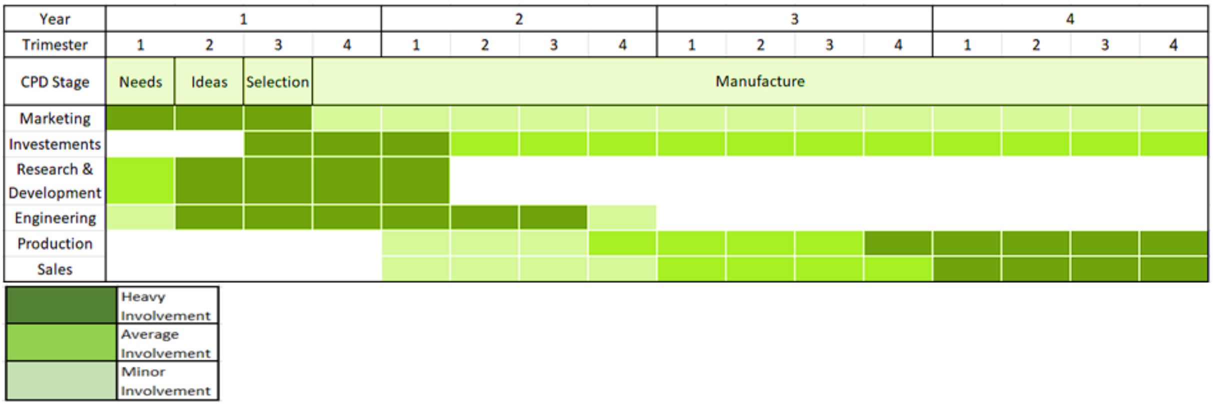

Figure 5: Gantt Diagram.

The first year of product development is very intensive in many areas. During this phase, the marketing department is concerned with identifying the needs and wishes of potential buyers. Based on the surveys conducted, product ideas can be specifically selected by the R&D department to optimally satisfy the customers' needs. Technical activities also play an important role in product development. This department often makes the trade-off between innovation and demand and then creates the production schedule. At the end of the first year and the beginning of the second year, the first innovations are made. Investments include the purchase and selection of materials and equipment needed to produce the product. In addition, the marketing department and sales department work closely together to define a suitable approach to the market and then start production and sales in the second year. Due to a complete process, investments are reduced, minimizing expenses on materials, salaries and site rent. At the end of the second year, the sales of the product allow the company to become self-sufficient through the revenues. If the product remains constant on the market, the marketing activity can be minimized.

4.2. Warehouse

A warehouse of 3,852 m^2 in Agueda would be bought for around 340,000 €, that is, 88.27 €/m^2. This location was chosen because of the proximity to the kiwi producers, as well as the price of the water, seeing as the process relies heavily on it. The size of the warehouse took into consideration the need to stock the dry raw material.

4.3. Raw material

It was established that 30% of the national kiwi production, in other words, 3,000 tonnes, would be processed a year. The Kiwi branches were bought for 2 € per ton. This is a symbolic value just to make the kiwi producers deposit the branches in a specific location for pick up, instead of just throwing it in the trash or using it for other things such as composting. The total price of raw materials would come to 6,000 € yearly.

4.4. Transport

The drying process of the kiwi branches would be done in only 14 days. With this in mind, 10 trucks would be rented for the same amount of time, to pick up the raw material. The trucks chosen were from the model Mitsubishi Carter cab with a capacity of 1.6 tonnes, each with maintenance, driver and inspections included. This would mean a total cost of 30,308€ yearly. As for the gas, the trucks operate on diesel. Considering 1.601 €, the average price of diesel, it makes an additional 43,687 € a year.

4.5. Machinery

In order to make a more realistic approximation of the prices of the machines were consulted on Alibaba. An increase of 100% of the original machine price, covering additional taxes and insurance and shipping was also considered, resulting in a total of 289,918 €. Table 7 describes the costs of the equipment as well as the energy required for each machine. It is worth noting that the evaporator consumes no energy since it only uses the heat from the heating oil.

Machine	Cost (€)	Capacity (t/h)	Energy (kWh)
Shredder Machine	28,200	3	55
Dryer	22	2	4
Siever	3,196	0.6	0.55
Plastic roller	35,720	0.08	100
Digester (JTRFY3000)	16,920	1	2.2
Pulp washer	13,160	2.5	37
Evaporator	15,980	6	-
Causticizer Second furnace	54,520	1	18.5
Recovery reboiler	17,860	1	37
Screen	35,720	1	45
Furnace	54,520	0.9	18.5
Oil heater	14,100	0.12	43

Table 6: Cost, capacity and daily electricity consumption of each equipment

In addition, a maintenance cost of 50,000 € was considered.

4.6. Reagents

Table 8 details the quantity used for every reagent, as well as its prices and total cost per year.

Reagent	Quantity (tonnes)	Price (€/ton)	Final Cost (€)
NaOH	301.2	329	99,095
Na_2S	139.3	357	49,758
Na_2CO_3	73.5	150	11,054
NaOCl	90.9	301	27,343
$C_3H_8O_3$	136	752	102,272
Carvacrol	26.4	940	24,816
Starch	92.3	470	43,381
$Ca(OH)_2$	0.94	94	88
$CaCO_3$	1,646	94	154,724
Oil	1	4,230	4,230

Table 8: Semestral quantity, price, and total cost of each reagent.

Assembling all these individual costs, the reagents would come to 1,033,522 € yearly.

4.7. Electricity and Water

For this matter, a simulator from EDP was used to estimate the electricity price. It was assumed a simple time and a voltage of 20.7 kV, resulting in a power price of 0.6652 € a day and an energy price of 0.2596 €/kWh. Considering the energy consumption and operation hours of each piece of equipment, it was possible to calculate cost of energy, which would add up to a total of 26,284 € each year.

The total volume of water needed in a year would be 5,245.67 m^3. Assuming an average price of 1.86 €/m^3, the total amount of water used in a year would mean an expense of 9,758 €.

4.8. Wages

To meet the producing demand, the factory would need 3 shifts a day, each consisting of 2 workers and a supervisor in addition to an engineer working only one shift, as seen in Table 9. The total expense in wages would come to around 218,000 € a year.

Employees	Workers per shift	Shifts	Individual salary (€/year)	Total cost (€/year)
Operators	2	3	18,000	108,000
Supervisors	1	3	26,000	78,000
Engineers	1	1	32,000	32,000

Table 9: Number of workers and shifts and annual salaries and their total cost

4.9. Quality control

For quality control, a traction test would be performed daily by CINFU in order to access the bioplastics resistance. Each test costs 12 €, meaning a total cost of 4,032 € yearly.

4.10. Economic feasibility

To assess the feasibility of the project, it is necessary to take into consideration parameters such as Cash-Flow, NET Cash Flow, breakeven period and return of investment (ROI).

It is crucial to study the possible clients, such as retailers from the food industry, to define the market in which the company will be inserted. For this, 100,000€ would be allocated to place the company in the market, and an additional 20,000€ would be allocated yearly to maintain its position. These costs are shown in Table 10.

	Cost (€)
Warehouse	340,000
Machinery	289,917
Marketing campaign	100,000
Startup cost	116,201
Safety net	50,000

Table 10: Investment costs

By analysing the table, it is possible to conclude that the company will require an initial investment of 896,118€. This value would be obtained through bank credit. All credit is expected to be refunded in two years with an interest rate of 12%.

Each year, the total operational costs would equal to 1,438,098 €, Table 11. It is important to highlight that the first month would be to make the factory fully operational.

	Costs (€)
Raw material	6,000
Transport	73,995
Reagents	1,033,522
Water	9,758
Electricity	26,284
Machinery maintenance	50,000
Quality control	4,032
Wages	218,000
Marketing	20,000
IMI	1,020

Table 11: Yearly operational costs

By performing a market study, it was concluded that the average price of bioplastic film is around 0.05 €/m² which is a quite competitive and attractive compared to synthetic plastic films already on the market for roughly 0.04 €/m^2 (bioplasticsmagazine 2017). In order for the product to be profitable, it would need to be sold at 0.02 €/m^2. With this in mind, it was decided to sell the product at 0.04 €/m^2 to compete with the synthetic plastic market.

The present value cash flow (PV CF) and the NET present value cash flow (NET PV CF) were calculated for each trimester, as shown in Figure 6, considering a five-year analysis.

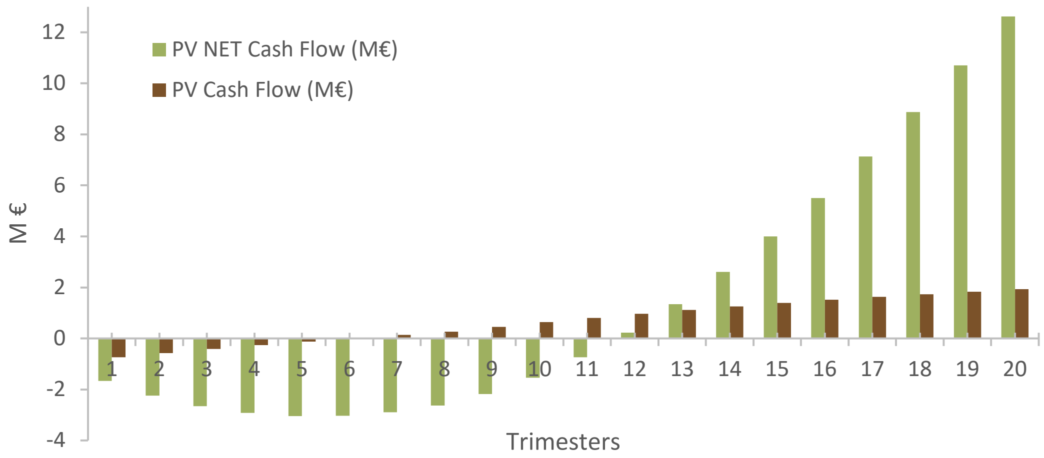

Figure 6: Each trimester's PV Cash Flow and the NET PV Cash Flow.

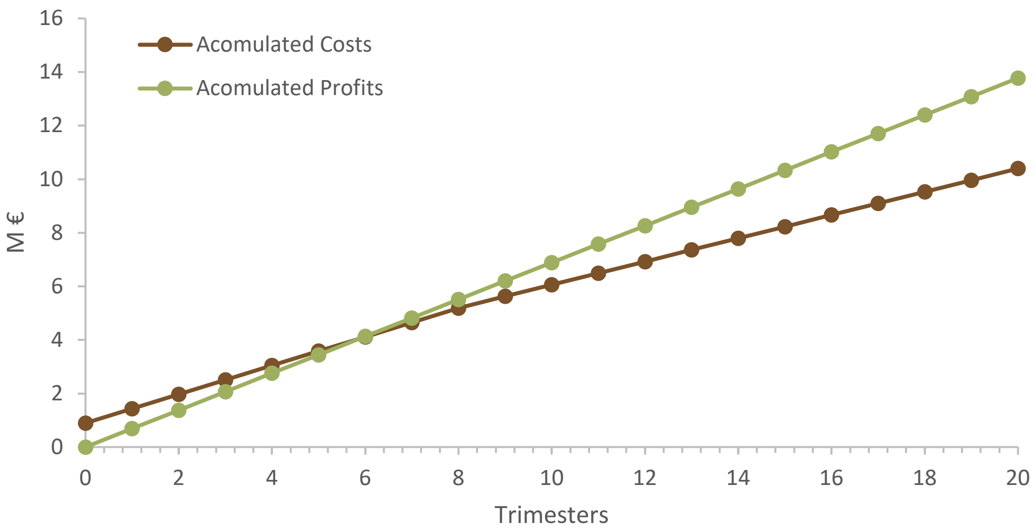

Figure 7: Accumulated costs and profits for each trimester.

5. Conclusions

Kiwiplast produces bioplastic films based on cellulose fibers from residue branches of the Portuguese national kiwi production. The product is designed for the final packaging of organic goods by other companies. The material stands out for being biodegradable in a scenario of growing public repulsion towards convenient plastic waste and uniting the qualities necessary for this kind of application, making it appealing for industries that want to invest in a greener public image. It was determined that an investment of 896,494 € would be necessary, the company would start operating at a profit and start paying off the debt in the sixth trimester and the updated cumulative monetary balance would become positive at the end of the twelfth trimester of the project. The amount of raw material to be processed annually would be 3,000 tonnes, and 1,102 tonnes of the final product would be produced, generating an income of 2,754,750€ a year, considering a selling price of 0.04 €/m^2 of film. In addition, it is estimated that a profit of 12.63 million euros over the duration of 20 years. It is thus possible to conclude that the project is economically feasible and attractive from a financial point of view and for generating value towards otherwise discarded waste and contributing to a circular economy.

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