ISA STEAM Year 10-13 : Design a biodegradable fabric for clothing
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Aim:

- To design a biodegradable material for clothing
- Create a bio yarn from sodium alginate (derived from seaweed) and calcium chloride
- Assess the performance, durability and cost effectiveness of the developed yarn

Introduction:

This competition caught our eye because the fashion industry is one of the largest polluters globally. It is responsible for 92 million tonnes of waste due to overproduction, chemical usage and energy intensive processes. The fast fashion industry encourages people to constantly buy new clothes and throw away old ones, further contributing to landfill waste. This then leads to a greater environmental impact, as textile waste produces 8% of greenhouse gas emissions, reducing biodiversity and increasing deforestation.

Energy-intensive processes are also used extensively in clothing production, particularly in countries like China and India where coal fuelled power plants are relied upon. This greatly increases greenhouse gas emissions.

Furthermore, waste from chemicals used in producing clothes, such as emulsifiers and dyes, are released into the environment harming marine life. One of the most damaging chemicals is polyester, made from petrochemicals. This is because it releases microplastics when being washed.

We wanted to take part in this competition because we enjoy finding creative solutions to real- world problems. We also loved that this competition bridged the gap between science and fashion and design. In our idea for sustainable fabric, we have used sodium alginate and calcium chloride, which react in a chemical process known as ionic cross-linking to form a gel- like material. This approach is both eco-friendly and innovative, as the materials are derived from natural sources and break down easily in the environment. Sodium alginate is a natural polysaccharide that is extracted from brown seaweed, and it is known for its gel-forming properties when it comes into contact with cations like calcium. It is also biodegradable, non-toxic and renewable. The manufacturing process requires minimal energy compared to synthetic fiber production and it breaks down safely without releasing microplastics, heavy metals or toxic residue.

Design journey:

Initially we had the idea of using sodium alginate and calcium chloride to create a bio plastic material because it offers several environmental benefits. Sodium alginate is derived from brown seaweed, making it a natural, biodegradable polymer. Unlike traditional plastics made from petroleum, alginate based bioplastic decomposes quickly, reducing the long term pollution in landfills and oceans. This also helps to combat the growing issue of microplastics that persists in ecosystems for hundreds of years. The raw materials are renewable, unlike fossil fuels that are conventionally used in plastic production. Seaweed also grows rapidly without the need for fertilizers or freshwater, making it a renewable resource. The process does not release harmful chemicals into the environment. Sodium alginate and calcium chloride are non-toxic and safe for both humans and wildlife. This would reduce the environmental contamination compared to traditional plastic manufacturing, which involves toxic solvents and high energy consumption. Furthermore, seaweed cultivation absorbs carbon dioxide from the atmosphere, helping mitigate climate change. Using seaweed derived materials indirectly supports this natural carbon capture process.

Therefore, because of all these benefits, we wanted to use these ingredients. Our first thought was to make a bioplastic material out of sodium alginate, pour the gel-like substance into molds and then spray the surface with calcium chloride solution and let it dry. However, the bioplastic can dry quite hard and we were worried that the outcome would not be flexible enough to be suitable for clothing. To overcome this, we came up with the idea of making a calcium chloride bath. We could then add the sodium alginate gel to a squeezy bottle and pour it into the bath. When the gel comes into contact with the calcium chloride bath, the bio yarn material is formed.

Cost effectiveness

The cost- effectiveness of making bio yarn for fabrics would depend on several factors, including raw material costs, production efficiency, scalability and market demand.

While the resources are renewable, they can be slightly more expensive due to farming, harvesting and processing costs. The cost of natural materials can also fluctuate based on agricultural conditions, supply chain issues, and demand. At a small scale, producing bio yarn can be costly due to a limited output and higher expenses, however, scaling up production would decrease costs through the bulk buying of raw materials and the use of more specialised machinery. Moreover, the fashion industry is shifting towards eco-friendly products, with consumers willing to pay a premium for sustainable fabrics. Even high-end brands are willing to pay the higher production costs due to the added value of sustainability. Overall, despite higher upfront costs, bio yarns offer long-term environmental benefits, potential brand value for eco-conscious companies, and alignment with future regulatory trends favouring sustainability.

Life cycle assessment

Raw material extraction

Source: harvesting brown seaweed (eg kelp)

Environmental impact: Generally low; seaweed farming absorbs carbon dioxide, promotes marine biodiversity, and requires no fertilizers or freshwater.

Production/ Manufacturing

Energy use: Moderate because of mixing and drying process

Water use: significant but water can be recycled in closed-loop systems.

Chemical waste: very minimal if managed properly, excess calcium chloride can cause localised water salinity issues only if not disposed of correctly.

Use phase

Environmental impact: Low; no microplastic shedding compared to synthetic fibres.

End of life (disposal)

Biodegradability: High; breaks down naturally in soil and aquatic environments without leaving toxic residue

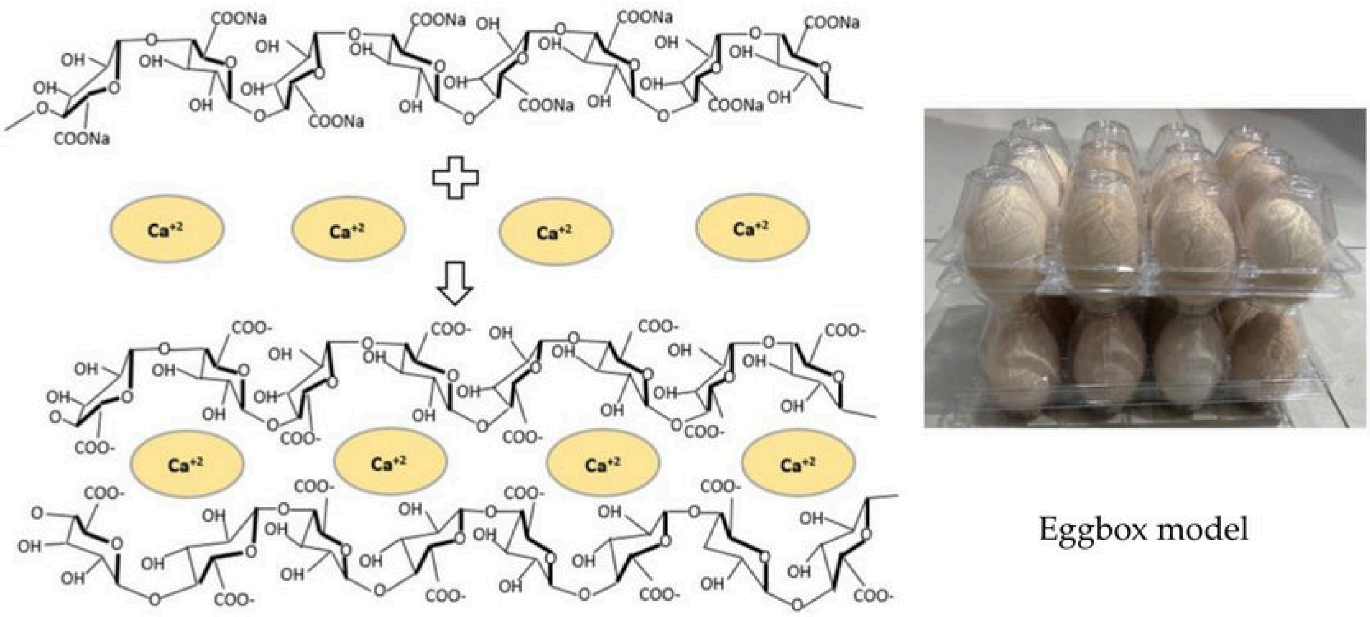
Composting: can be composted under industrial conditions

Hypothesis:

When sodium alginate is dissolved in water, sodium alginate should form a viscous solution due to the interaction of its long polymer chains with water molecules. The calcium chloride provides calcium ions, which replace the sodium ions in alginate. The calcium ions should interact with the guluronic acid blocks in the alginate chain, to form ionic- cross links between the polymer chains (Figure 1) . The chemical equation is given below:

$$2NaC_6H_7O_6 + CaCl_2 \rightarrow 2NaCl + C_{12}H_{14}CaO_{12}$$

Hopefully, this cross-linking reaction transforms the alginate solution into a flexible yet solid structure that will hold its shape as a yarn.



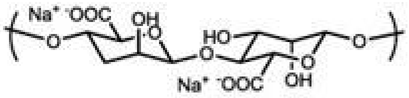
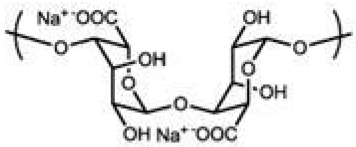
$$2NaC_6H_7O_6 + CaCl_2 \rightarrow 2NaCl + C_{12}H_{14}CaO_{12}.$$

Figure 1- Skeletal diagram of the reaction between sodium alginate and calcium chloride

Once dipped into the calcium chloride solution, the calcium ions will start to displace the sodium ions from the alginate. This will exert a greater electrostatic force of attraction on the carboxylate anions on neighbouring chains. These are the interactions that form the cross links between the chains, forming a gel like structure.

There are two types of sugar that make up the polysaccharide alginic acid (sodium alginate is the sodium salt of alginic acid). These are (1-4)-linked β-d- mannuronate (M) and α-l-guluronate (G). There are repeating subunits of G that form a zig- zig structure in which the calcium ions can sit on, which helps the cross-linking (Figure 2).

Figure 2- β-d- mannuronate (M): left and α-l-guluronate (G): right

<u>Apparatus</u>:

Materials and apparatus used	Uncertainty	Quantity	Justification
Weighing boat	N/A	x2	The calcium chloride and sodium alginate were transferred on to the weighing boat that was on an electric weighing balance using a spatula to accurately measure the mass.
Electronic weighing balance	±0.01 g	x1	To measure the mass of sodium alginate and calcium chloride
Spatula	N/A	x2	To transfer sodium alginate to mixing bowl and the calcium chloride to the container
100 cm^3 graduated measuring cylinder	±0.05 cm^3	x1	To measure and transfer water
Electric hand mixer	N/A	x1	To blend the sodium alginate, vegetable oil and glycerin into a paste
Squeezy bottles	N/A	x1	To transfer the paste into the calcium chloride solution
Mixing bowl	N/A	x2	To mix ingredients
Cling film	N/A	x1	To cover the mix overnight
Food colouring (can be substituted for food as a natural dye, ie. Beetroot)	N/A	x1	To add colour to the bio yarn
Fridge	N/A	X1	To allow the mix to settle overnight
Crochet hook	N/A	x1	To crochet the bio yarn
Baking paper	N/A	x1	To place the bio yarn on whilst it dries

<u>Materials and risk assessment:</u>

Name of chemical	Hazard symbol	Hazard danger	Precaution
Sodium Alginate		Hazardous if inhaled	Wear eye protection, wear a lab coat
Vegetable glycerin		Hazardous if inhaled	Wear eye protection, wear a lab coat, wear gloves (optional)
Calcium chloride		Hazardous if inhaled, could be an irritant if it comes in contact with skin	Provide adequate ventilation, wear eye protection and lab coats
Vegetable oil	Not hazardous	Only hazardous if heated	Avoid spillages

<u>Method (subject to alterations):</u>

1) Measure out 12±0.01 g of Sodium alginate and 20±0.01 g of vegetable glycerin.
2) Pour both into a bowl and mix well.
3) Then, add 10±0.01 g of sunflower oil and use a glass rod to mix until combined.
4) In a separate bowl, add 400±0.05 cm^3 of water and 4 drops of food die, mix until combined.
5) Add the water and dye mix to the sodium alginate mix and use a hand blender to mix until it forms a paste with no lumps.
6) Cover it with cling film and place it in the fridge to let it settle (for about an hour, or overnight)
7) In a separate bowl, make a 10% calcium chloride solution. For ours, we used 40±0.01g of calcium chloride and 400±0.05 cm^3 of water.
8) Pour the sodium alginate mix into a squeezy bottle using a funnel.
9) Consistently squeeze the mixture into the calcium chloride solution and a yarn-like structure should form.

<u>Trial 1</u>

Evaluation

On our first try of the experiment, we encountered some difficulties. First of all, we added the food dye straight into the sodium alginate mix, instead of mixing it with water first. This caused it to clump together and it did not disperse throughout. However, a light colour was obtained. We also did not have a hand blender which was a problem when we tried to make the sodium alginate paste. Water is a polar molecule and vegetable oil is a non polar molecule and due to their different polarities, they do not mix. Instead, the oil formed a distinct layer on top of the water because it is less dense. When we added the water to the sodium alginate paste, without a hand blender, it was very difficult to mix. Glycerin is very viscous and has strong intermolecular forces, also making it mix very slowly with water. Additionally, the hole on our squeezy bottle was not big enough so it was hard to get a continuous flow of the paste. Air bubbles often formed and sometimes the paste would break off, making it hard to get a full strand. However, we still persevered and the experiment did work, but it was in need of some tweaks before day 2.

Adjustments to method for trial 2

- Use a hand blender to mix the sodium alginate gel
- Mix the food dye with water before adding it to the gel
- Cut a wider hole on the nozzle of the squeezy bottle for a more continuous flow

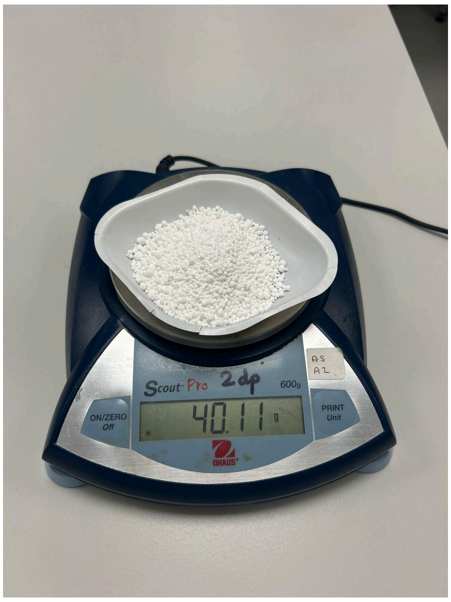


Figure 3a

Figure 3b

Figure 3c

Figure 3. Method used to make the bio yarn. 3a measuring calcium chloride on the electronic weighing balance, 3**b:** sodium alginate mix before adding water, undissolved food colouring can be observed, **3c:** first attempt of squeezing sodium alginate mix into calcium chloride bath, large lumps were evident.

<u>**Trial 2**</u>

Evaluation

The next day the string we had made during trial 1 had dried up and become very thin. Therefore, we cut a wider hole on the nozzle. However, we still used the same sodium alginate paste from the day before, which allowed it to settle overnight. This ensured the removal of air bubbles which helped improve the flow, making it more continuous. A yarn was obtained which enabled us to crochet, highlighting its flexibility as well as its durable nature. However, we did notice a slight problem with the bowl we were using for the calcium chloride bath. We used a deep dish as we thought the yarn would sink, however, it floated. Due to this, when the yarn rises to the top, some parts would be out of the solution and this causes protrusions on the yarn. It was difficult to cut the protrusions as there was still liquid inside. We also could not wait until it dried because it had to be crocheted while it was wet. In order to overcome this, we decided to use a wider rectangle dish. This allowed us to have a bigger area to work with, and it meant that the yarn did not get tangled.

Figure 4a

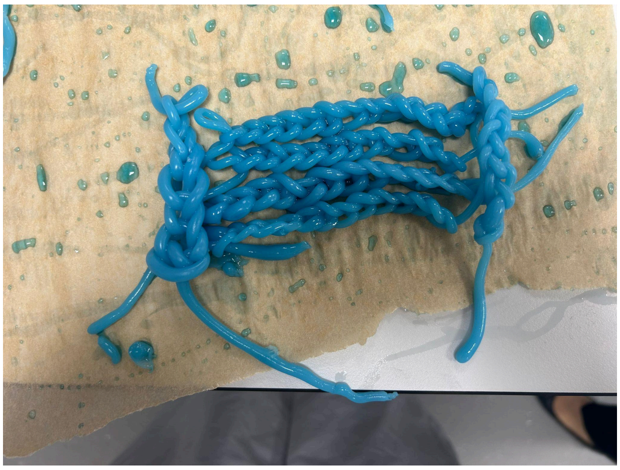


Figure 4b

Figure 4- 4a: Trial 1 bio yarn left overnight, dried up very thin, **4b:** Attempt 2, using a thicker nozzle and larger calcium chloride bath. Strands have been crocheted.

Adjustments to method for trial 3

- Leave the alginate gel overnight to settle
- Use a wider dish for the calcium chloride bath

<u>Trial 3</u>

Evaluation

We made a new sodium alginate paste and used a hand mixer which made the paste a lot smoother. We also mixed the food dye in with the water beforehand, making the colour a lot richer. We used the bigger nozzle and got a better flow. We managed to crochet quite a few pieces and even attempted to use the smaller ones from day to weave the crocheted pieces together. We used a vernier caliper to measure the diameter of the bioplastic.

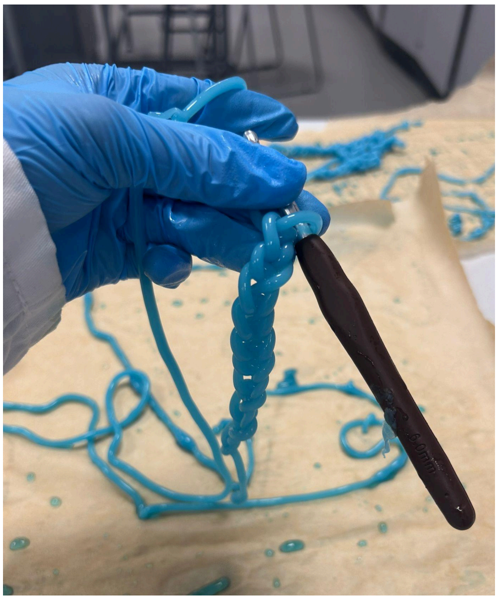


Figure 5- Crocheting the bio yarn with a 6mm hook

<u>Method</u>

1. Firstly, the jaws of the vernier caliper were opened and the bioplastic was placed between the jaws.
2. The jaws of the caliper were pushed against the bioplastic sample and the clamp was locked, to secure the jaws.
3. The readings of the caliper were recorded.
4. The main scale, which is the last whole increment visible before the 0 mark was recorded. The secondary scale measurement, which is the division that lines up with the marks on the main scale, was also recorded.
5. Finally, both readings were combined to work out the thickness of the bioplastic.

The width was recorded at 2.20 mm. This was consistent throughout the length of the yarn and the reading was taken 3 times to ensure that the data collected was reliable. To ensure that parallax error was avoided, the reading was taken from the same position, perpendicular to the vernier caliper (Figure 6).

<u>**Trial 4**</u>

We wanted to test the strength and durability of our biodegradable fabric, and in order to do that we carried out the Hooke's Law Experiment.

Figure 6- measuring the diameter of the bio yarn using a vernier calliper

What is Hooke's law?

Hooke's Law states that the force needed to extend or compress any elastic object, is directly proportional to the displacement of the object from its original position.

We decided to use the Hooke's Law experiment to investigate the strength of our bio yarn and to determine how much weight it can hold before it breaks.

Independent variable- Amount of mass (g)
Dependant variable- The extension of the bio yarn (cm)
Controlled variable- The length of the bio yarn and the mass of the bio yarn

Materials and apparatus used	Uncertainty	Quantity	Justification
Stand	N/A	x1	Provides stability, ensuring accurate, consistent measurements without movement.
Ruler	±0.05cm	x1	To measure the extension of the bio yarn
Slotted masses	±0.5g/±5g	x10 (of each set)	To apply known forces to the bio yarn
Mass hanger	±0.5g/±5g	x1 (of each)	To hold the slotted masses

<u>**Method**</u>:

1. Attach the biodegradable material to the holder
2. Attach a ruler to the holder so that the start of the material lines up with 0
3. Record the initial length of the material, make sure to read the ruler at eye level to avoid parallax error
4. Add a 10g mass to the material and record the new length of the material, taking away the initial length
5. Keep adding 10g masses until the material breaks to test its durability

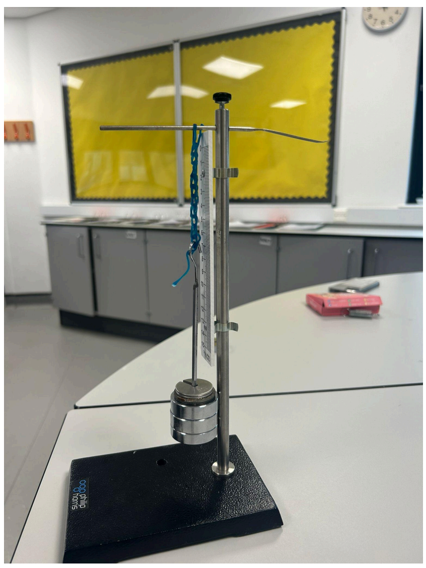


Figure 7- Hooke's Law experiment on crocheted bio yarn

Risk assessment:

Equipment	Hazard	Precaution
Masses	Could fall when suspended above the ground, leading to potential injury	Stand away from the clamp stand when adding the weights, ensuring our hands are not beneath.
Clamp stand	Could topple if too much weight is added and fall, leading to potential injury	Stand far away from the setup when adding masses

Results:

Extension = Final length - initial length

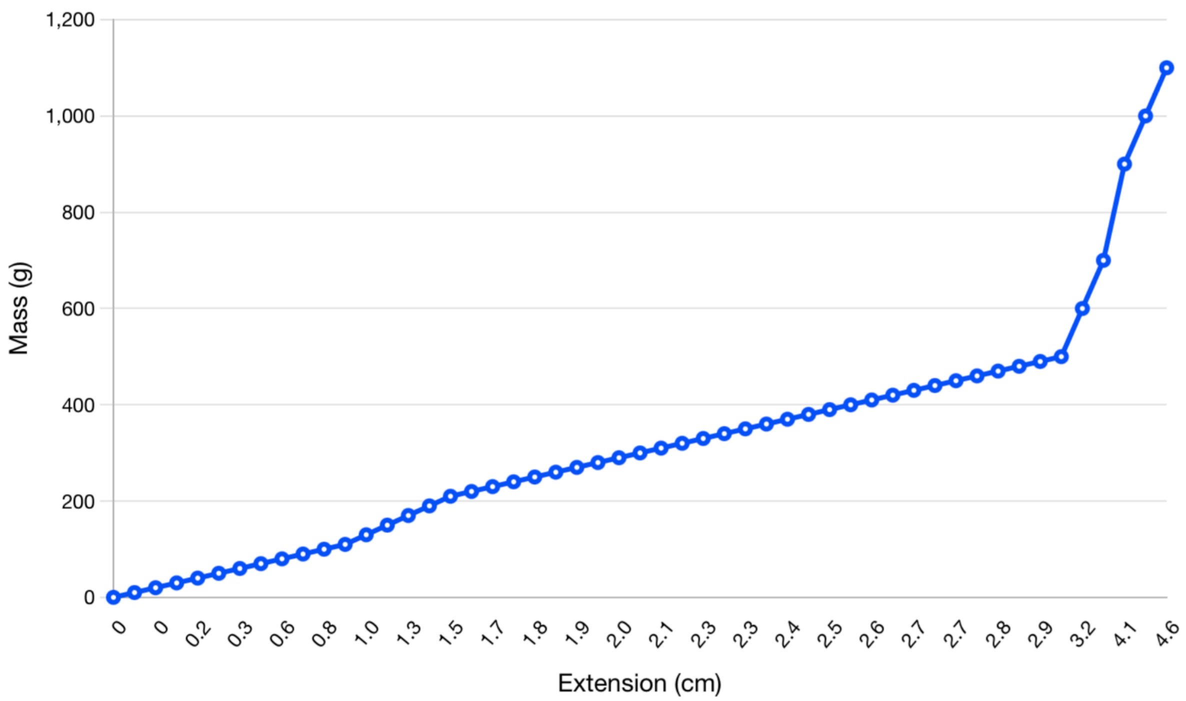
Sample calculation for our 3rd data set:

8.4cm - 8.2cm = 0.2 ±0.02cm

Mass (g±0.01)	Length (cm ±0.01)	Extension (cm ±0.02)
10	8.2	0.0
20	8.2	0.0
30	8.4	0.2
40	8.4	0.2
50	8.4	0.2
60	8.5	0.3
70	8.6	0.4
80	8.7	0.5
90	8.8	0.6
100	9.0	0.8
110	9.0	0.8
130	9.0	0.8
150	9.2	1.0
170	9.2	1.0
190	9.5	1.3

210	9.7	1.5
230	9.8	1.6
250	10.0	1.8
270	10.1	1.9
290	10.2	2.0
300	10.2	2.0
400	10.7	2.5
500	11.1	2.9
600	11.3	3.1
700	11.4	3.2
800	11.5	3.3
900	11.9	3.7
1000	12.3	4.1
1100	12.6	4.4
1200	12.8	4.6

Figure 8 - A graphical representation of Mass (g) (or Force) against Extension (cm)



Cross section area (m^2) = 4.84×10^{-4}
Weight (N) = 1200 x 10/1000 = 12N

Tensile strength = 24,793.39 Nm^{-2}

Tensile Strength

The tensile strength is the measure of the ability of the bioplastic to resist a force that pulls it apart. It took an extension of 4.6 cm and 1200g of mass for the bioplastic to hold, until it ripped off. The tensile strength was quite high (24,793.39 Nm^{-2}) in relation to its cross sectional area, which is fairly small. This revealed that the bioplastic was able to carry a large amount of weight before snapping, which is an important quality for a plastic to obtain for wider applications.

Evaluation

We found that the fabric could hold up to 1.2kg before snapping, showing its high tensile strength and durability. Furthermore, the interlocking chains formed through crocheting the material allowed it to be even stronger and stretch more without snapping. Overall, the material extended 4.6cm after adding 1.2kg. The force (F) vs. Extension (x) graph shows a straight line region at the start, confirming that the biodegradable yarn follows Hooke's law within this range, where deformation is elastic and proportional to the applied force.

Trial 5

In the final trial, we decided to test the water and pH resistance of our material using three solutions of varying pHs - Water, Sodium Hydroxide and Hydrochloric acid.

Water absorption and pH resistance test

We decided to record the moisture resistance of our material to investigate how it would affect its size and shape. We also decided to test the material in acidic and alkaline solutions to further test its resistance. This is because acidic or alkaline chemicals are likely to come into contact with the material as an item of clothing in everyday use. For example, our sweat is slightly acidic, possibly having an effect on the material, as well as alkaline chemicals present in packaging.

Method

1. Cut one sample of the material into three, equal sized pieces, measured with a ruler.
2. Measure the initial mass of each of these pieces using a weighing scale and record.
3. Using a measuring cylinder, measure 50±0.05cm^3 of distilled water, sodium hydroxide (1M) and hydrochloric acid (1M) and place in three separate beakers. Clearly label the chemicals.
4. Place each material segment into each beaker and set a timer for 1 hour and 15 minutes.

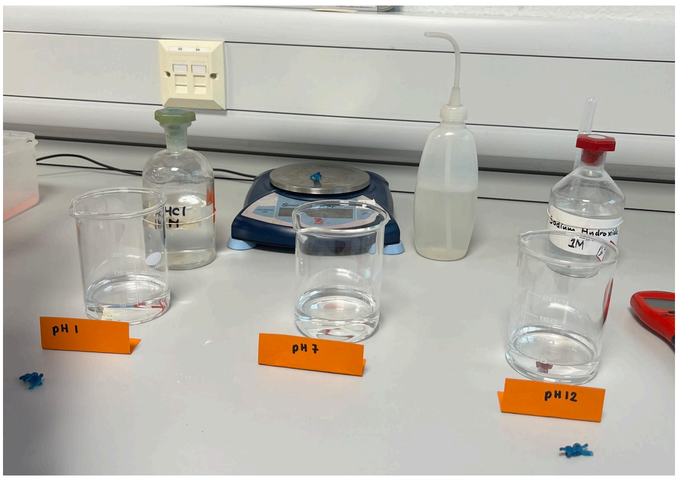


Figure 9- the segments of crocheted bio yarn in pH 1, pH 7 and pH 12

5. After 1 hour and 15 minutes, dry each bioplastic yarn in paper towels, then reweigh each material segment and record the new mass.
6. Calculate the change in mass for each piece, which was recorded 3 times.

Risk assessment

Chemical	Hazard	Safety precaution
Sodium Hydroxide	Corrosive Harmful	-Wear safety goggles and a lab coat -Only use small amount ($50cm^3$)
Hydrochloric acid	Corrosive Irritant	-Wear safety goggles and lab coats -Only use small amount ($50cm^3$)

Results

Solution	Initial mass of material (g±0.01)	Final mass of material (g±0.01)	Change in mass of material (g±0.02)
1M Sodium Hydroxide (pH 12)	0.28g	0.32g	0.04g
Distilled water (pH 7)	0.33g	0.44g	0.11g
1M Hydrochloric acid (pH 1)	0.30g	0.37g	0.07g

Evaluation

In conclusion, the mass of the material changed the most after being placed in distilled water 0.11±0.01g. If the bioplastic yarn was exposed to water for 15 minutes, the change in mass would be around 0.022g. This is a very insignificant difference, displaying how a short amount of time in water would have little effect.

Furthermore, the values of the change in mass for Sodium hydroxide and hydrochloric acid are very low, suggesting that the material is suitable for most acidic and alkaline conditions. This is ideal for use in industry as many packaging materials are made from alkaline chemicals, so packaging our material would not cause significant damage to its structure.

Conclusion

We were both happy and excited about how our experiment came out. Our bio yarn made from sodium alginate and calcium chloride is an exciting innovation for sustainable fashion. Through ionic cross- linking, flexible fibres were created, offering an eco-friendly alternative to synthetic fabrics.

Through our numerous tests of tensile strength, water resistance and pH resistance, we were able to observe that our bioplastic is strong and durable as well as having little impact when exposed to small amounts of alkaline and acidic conditions. Therefore, it is an ideal choice for a biodegradable material in industry.

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