Reflow

constRuctive mEtabolic processes For materiaL flOWs in urban and peri-urban environments across Europe

Bio-based textiles in a circular model

Next Steps

REFLOW MATERIOM

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I. INTRODUCTION TO CIRCULAR TEXTILES

The environmental crisis resulting from our current production system is more critical than ever before. This highly intensive process has reached a point where it has been polluting our planet and endangering the survival of the human species due to depleting resources that have been consumed for centuries and not foreseeing the implications for future production. This is why several trends, such as Cradle to Cradle, the Circular Economy, and Doughnut Economics, propose new practices and guidelines that promote sustainable and regenerative social and environmental models.

One of the most complex issues is plastic pollution, a material widely used in packaging, construction, textiles, and consumer goods (Rosenboom et al., 2022). After a short use phase, most ends up in the environment through landfill and litter. This leads not only to macro pollution but also to microplastic contamination, which has been found in animals and, most recently, the human bloodstream (Carrington, 2022). Most ocean microplastics are from land pollution, where around 35% are from washing synthetic clothes (SAPEA, 2019).

Regarding the textile industry, there are several initiatives today that address a more circular approach to the textile industry throughout the supply chain (Luiken et al., 2021). **Sustainability is not only about materiality but also includes the sourcing of the resources, the use, reuse and recycling of the materials, the transparency of the process for consumers, and the overall energy used in the whole cycle.** There has also been an increasing urge for innovative bio-based textile materials. In the following document, we aim to break down this new trend into sub-areas, seeking to understand whether there is a demand for them today and how they could provide more sustainable solutions. This chapter considers some of the latest reports and research on the subject and is structured by the discussions in the context of the Reflow project through which the city of Amsterdam piloted innovative approaches to circular textiles.

II. INTRODUCTION TO BIO-BASED MATERIALS

According to the EU Commission (2020), **bio-based materials are "fully or partially made from biological resources, rather than fossil raw materials."** This definition highlights that not all these bio-based materials are biodegradable or compostable. A thorough examination needs to occur throughout the life cycle to assess the impact of each material on the environment. Moreover, biodegradable or compostable materials are not always bio-based as degradation can be on the basis of a material's chemical structure and not necessarily its organic composition. This characteristic means that both biomass-based and fossil-based materials can be biodegradable, highlighting the importance of having a more comprehensive method of analysis.

The Ellen McArthur Foundation (EMF, 2017) proposed biological and technical production cycles within their definition of a circular economy. **The biological cycle focuses on the use of renewable resources and by-products which can biodegrade and reintegrate into nature's cycle.** At the same time, the technical cycle concerns the sustainable management of highly processed materials.

Authors like Rosenboom, Langer & Traverso (2022) have analysed the advantages and challenges of bio-based materials for promoting a circular economy. **Bio-based materials have the potential to show a lower carbon footprint than fossil-based plastics, besides being compatible with strategies more friendly to the environment like recycling and biodegradation processes.** However, there are some drawbacks such as expense, competition with food security, and unclear strategies for closing their cycle.

Cotton field - Kimberly Vardeman, CC BY 2.0

III. DEMAND AND CONSUMERS

A key aspect to consider is the real need and demand for 100% bio-based materials. In 2021, the global **bioplastic market produced ~2 million metric tons**, and is **projected to be producing 3.3 million metric tons annually by 2026**. Moreover, these numbers rise to more than **7 million tonnes if partially bio-based materials are included**, likely to reach nearly **9 million tonnes by 2023** (Rosenboom et al., 2022). As mentioned previously, there is increasing pressure for more sustainable materials for fabrication, which is a combination of consumers' and brands' demands alongside updated regulations. Also, biomaterials are considered a strategy for meeting the SDGs -specifically decreasing the quantity of toxic chemicals in production, encouraging recycling and degradation schemes, and shifting from non-renewable sources such as fossil-fuel resources to renewables (Karan et al., 2019).

In response to this, several brands and customers are seeking bio-based options. However, there is a large degree of misinformation due to a lack of standards, regulations and guidelines. For example, labels for biomaterials are mostly related to their recyclability, whether they contain biomass, or whether they are biodegradable or compostable. Unfortunately, this system changes from country to country and does not consider the real possibilities of recycling or composting a product locally (Rosenboom et al., 2022).

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IV. SOURCING BIO-BASED RESOURCES

A common drawback with bio-based materials is the potential competition with food for human or animal consumption. This competition refers especially to first-generation feedstocks like crops and plants. Consequently, a **more suitable source for biomaterial production is second and third-generation feedstocks** (Barret, 2018). Second generation refers to feedstocks not ideal for consumption, like inedible parts of crops, byproducts from first-generation feedstock processing, and domestic waste. At the same time, third generation refers to algae, which are advantageous given the ease of cultivation and ubiquity.

In the context of the Reflow Project (2021), the organic waste from Amsterdam, Milan and Vejle was analysed focusing on second generation biomass, dividing it into avoidable (AFW) and unavoidable food waste (UFW) (Coudard et al., 2021). AFW is defined as edible food which has been discarded, while UFW refers to inedible food products (e.g. peels, bones, skins, and inedible fats). Within Reflow, UFW was analysed to calculate the percentage of available biopolymers that could be used for biomaterials production. Amsterdam's UFW and biopolymer availability can be reviewed in the following tables.

Table 1 - Amsterdam Unavoidable Food Waste Diagram - Metabolic

Poultry Meat	*3416.63*	Apples & Products	*967.42*	Mutton & Goat Meat	*62.75*
Coffee & Products	*3044.85*	Tea	*543.67*	Grapes & Products	*52.77*
Banana & Plantains	*1529.88*	Bovine Meat	*499.94*	Fish	*9.68*
Potatoes & Products	*1471.79*	Pineapples & Products	*320.36*	Dates	*5.65*
Pigmeat	*1426.97*	Grapefruit & Products	*251.70*	Crustaceans	*1.56*
Eggs	*1083.68*	Onion	*86.99*	Molluscs	*0.49*
Orange & Mandarines	*1006.73*	Lemon, Limes & Products	*76.70*	Cephalopods	*0.18*

UFW Model by Metabolic (Coudard et al., 2021). Data source from: Food Balance Sheet (2017), FAO global food waste estimate (2011), De Laurentiis et al. (2018), WRAP (2014), John-Jaja et al. (2016).

Table 2 - Amsterdam Biopolymer Availability per UFW tons Diagram - Materiom

Unavoidable Waste	*Tons*		*Biopolymer*	*Tons*
Poultry Meat	3416.63	→	Collagen (Gelatine)	512.49
Coffee & Products	3044.85	→	Cellulose	261.86
			Hemicellulose	1117.49
Bananas & Plantains	1529.88	→	Cellulose	183.59
			Hemicellulose	344.53
			Starch	229.48
			Pectin	382.47
Potatoes & Products	1471.79	→	Starch	294.36
Pigmeat	1426.97	→	Collagen (Gelatine)	85.62
Eggs	1083.68	→	Calcium Carbonate	1029.49
Oranges, Mandarines	1006.73	→	Cellulose	115.27
			Hemicellulose	109.73
			Pectin	180.71
Apples and products	967.42	→	Cellulose	85.23
			Hemicellulose	52.63
			Pectin	66.27
Tea (including mate)	543.67	→	Cellulose	86.99
Bovine Meat	499.94	→	Collagen (Gelatine)	30.00
Pineapples and products	320.36	→	Cellulose	54.33
			Hemicellulose	39.21
			Pectin	9.80
Grapefruit and products	251.70	→	Pectin	54.12
Onions	86.99	→	Cellulose	39.14
			Hemicellulose	17.40
Lemons, Limes & Products	76.70	→	Pectin	12.04
Grapes and products (excl wine)	52.77	→	Cellulose	5.54
			Hemicellulose	3.22
Mutton & Goat Meat	62.75	→	Collagen (Gelatine)	3.77
Fish	9.68	→	Collagen (Gelatine)	0.97
Dates	5.65	→	Cellulose & Hemicellulose	4.75
			Pectin	0.34
Molluscs & Crustaceans	2.06	→	Calcium Carbonate	0.72
			Chitin	0.31

Biopolymer availability in UFW by Materiom. Data Source for UFW from Coudard et al., 2021.
Data Source for biopolymers from: Source: Arbia et al., 2012; Gorgieva & Kokol, 2011; Homester et al., 2012; Hue, Minh Hang & Razumovskaya, 2017; Nys et al., 2004; Suresh et al., 2016; Szymańska-Chargot, 2017; Torres et al., 2020; Pareek, 2016; Prasad & Rhim, 2018; Rodriguez & Castro, 2019; Wongsiridetchai et al., 2018; Yang & Shu, 2014; Zhao et al., 2018.

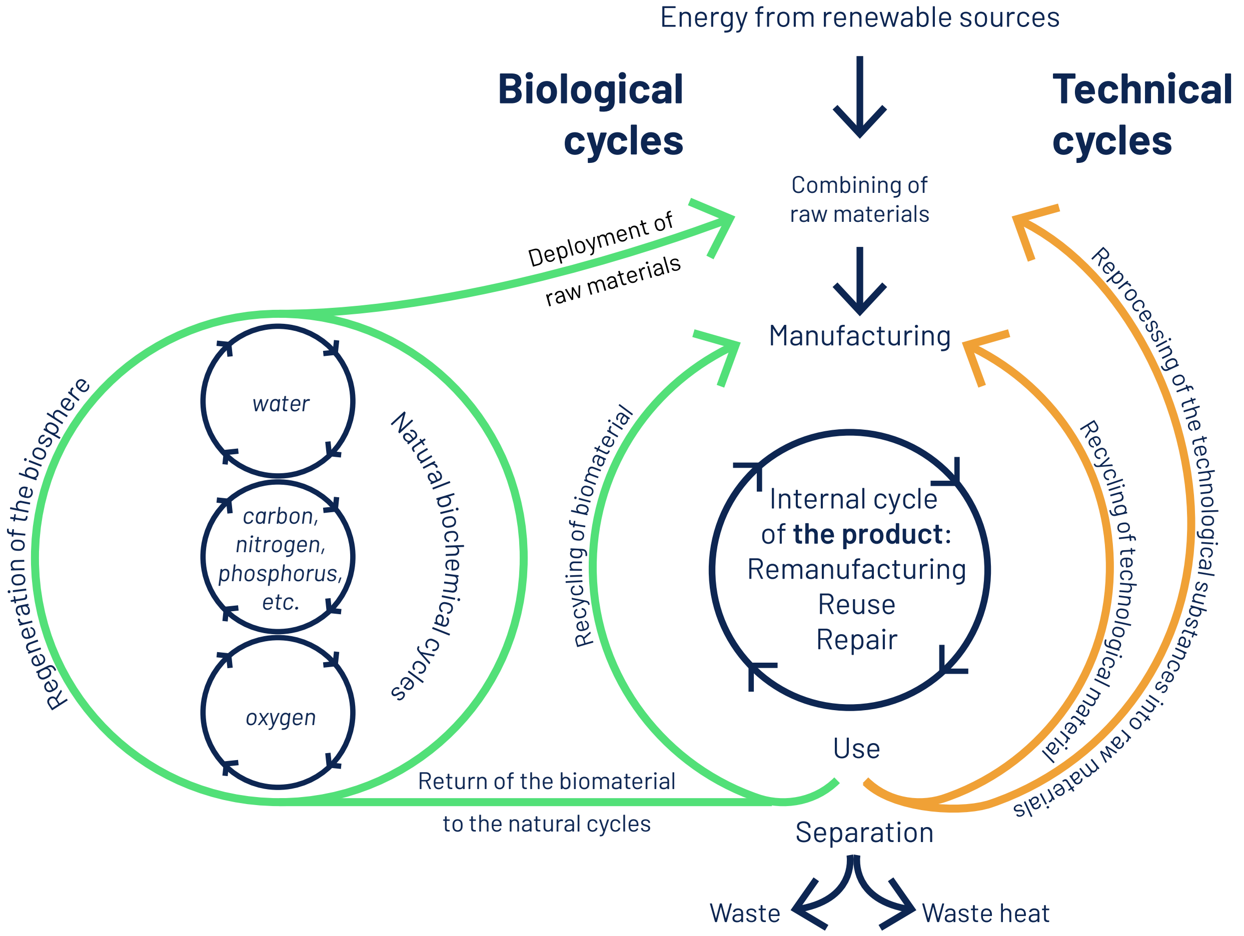
The previous information serves as an argument to boost the biomaterials industry further. **There is a growing demand, but there is also a pivotal opportunity to source untapped resources from underutilised second generation biomass.** It's important to consider the amount of embedded value in this "waste," where human hours, water, energy, and transport have been invested. In the context of Amsterdam, it's advantageous to review the opportunity of **UFW biomass as a resource for the textile industry.** However, a circular supply chain must also be created to use this resource efficiently. Biomass is sensitive to ambient conditions, and there are issues of adequate timing, sorting, preprocessing, and transport that should be considered. Moreover, it is necessary to understand the different scales of producing biomaterials -ensuring each scale of production follows regenerative guidelines.

V. PRODUCING BIO-BASED MATERIALS

A. Biomaterials and Textiles Chemistry

The **development of regenerative, biocompatible systems for commercially driven applications should closely observe life-friendly chemistry principles which strive to align with nature's genetic lifecycle.** This includes utilising biopolymer precursors that are symbiotic to ecological processes. It is also possible to chemically engineer or tune biochemical processes through green chemistry -modifying and adapting biomaterials to possess properties suitable for diverse industrial applications. These include **adapting materials to local ecologies using readily available low energy-intensive and cyclic processes, whereby products break down into benign constituents.**

Diagram 1 - Biological Closed Loop
University of Helsinki Diagram



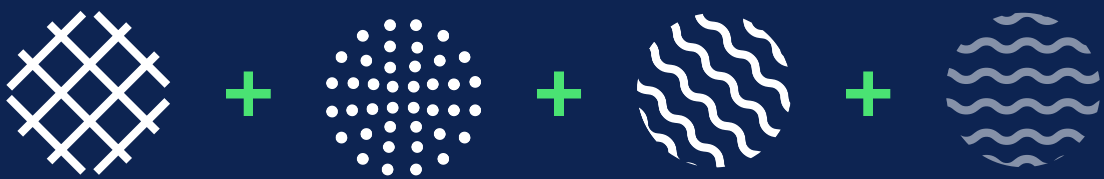
B. Biomaterials System

In the context of Reflow, **a set of biomaterial systems was prototyped and formulated for the pilot cities, aligning the production methodology with life-friendly chemistry principles** (Dorfman, 2012). For this, four biopolymers were chosen from the UFW and biopolymer availability analysis. First, **cellulose, gelatine and starch** were selected because of their large availability within the biomass waste. In addition, **chitin** was selected because of its high market value. While not available in large quantities at the urban UFW level, chitin is the second most naturally abundant biopolymer in our biosphere. Literature demonstrates the desirable properties it can have when used for biomaterials. Moreover, it is possible to harvest chitin from black soldier flies which feed on mixed organic waste (Sanandiya et al., 2020), offering the potential to link its production to UFW.

The biomaterial systems generated for the pilot cities are as follows:

Table 3 - Biomaterial systems composition

1.1	*Methyl-cellulose Chitin*	–	*Glycerol*	*Water Vinegar*
2.8	*Methyl-cellulose Gelatin*	–	*Glycerol*	*Water*
3.1	*Methyl-cellulose Potato Starch*	–	*Glycerol*	*Water Vinegar*
	Structural Matrix	***Filler***	***Plasticizer***	***Solvent***
	Biopolymer that agglomerates the material	*Fibre or mineral that fills in the material, enhancing specific properties*	*Biopolymer that enhances the flexibility and strength of the material*	*Dissolves the main components that promote chemical catalysis*



These material systems were developed through co-polymerisation of the structural matrix precursor to provide tunable structural and mechanical properties based on variations in the component ingredients. Please refer to *Sections III & IV of the Material Development & Properties Report at Reflow project platform* for more information on the material systems.

C. Properties Analysis & Potential Applications

The mechanical properties of the material systems described previously were assessed using a commercial **tensile testing machine** (for a more detailed overview of the biomaterial samples and their properties, please refer to Appendix 1 and the Material Development & Properties Report). The initial mapping of these mechanical properties can be used as a preliminary indication of how they compare to traditional market materials and their potential applications.

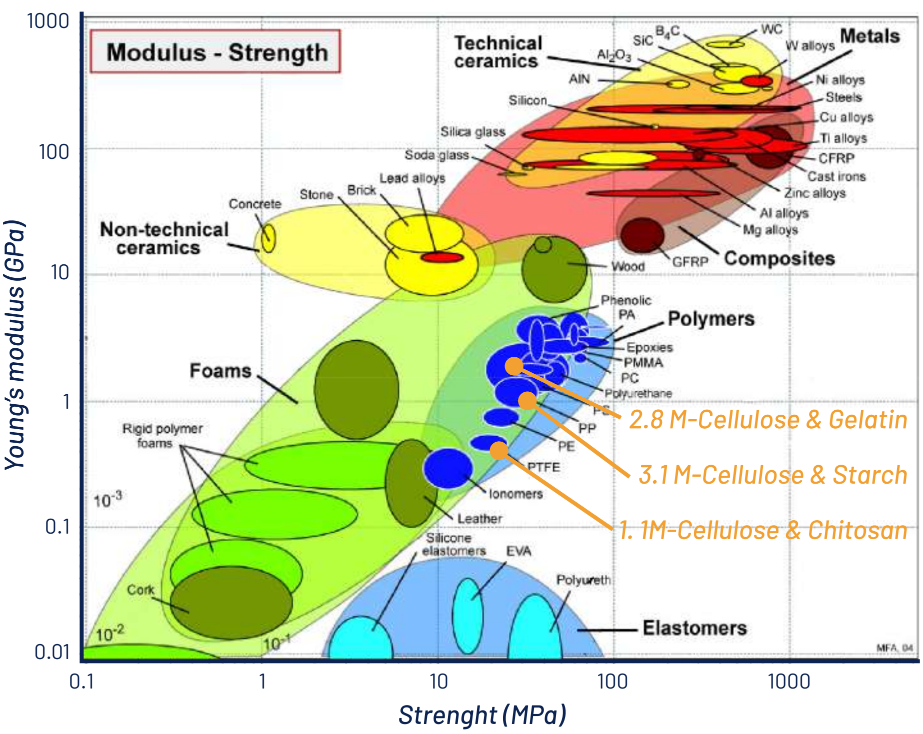
Represented here (Diagram 2) is an Ashby diagram that highlights the **Young's Modulus**[1], against **strength**[2]. The Ashby diagram maps the material properties of diverse material systems (Ashby, 2010), compared to the material systems developed from UFW biomass within the Reflow project.

As shown in the Ashby diagram the prototyped material systems are comparative to the performance of known petrochemical derived plastics such as Polypropylene (PP), Polytetrafluoroethylene(PTFE), PMMA Poly(methyl methacrylate), utilised for **packaging and textile applications** (Sangroniz et al., 2019).

1 *Young's modulus: a material's resistance to deformation or compression after an applied force maximum*
2 *Strength: the maximum strength a material can withstand upon elongation before breaking*

Diagram 2 - Young's modulus against Strength.

Ashby (2010). Material and process charts. Chart 3.



Highest Performing Samples*:
1.1 Methyl-Cellulose Chitosan 489MPa = 0.489 GPa
Comparative to Foam - Polymers area

2.8 Methyl-Cellulose Gelatine 1092MPa = 1.092 GPa
Comparative to Polymers area

3.1 Methyl-Cellulose Starch772MPa = 0.772GPa
Comparative to Polymers area

**1 Megapascal (MPa) = 0.001 Gigapascal (GPa)*

** Regional Reference Point*

While the identification of applications requires further research, the mechanical properties obtained suggest good alignment with **packaging, interior upholstery, binders industries, and sizing**[1] **for textiles** (Wenqiang et al., 2019). This preliminary data shows that the combining of cellulose-derived compounds with an accompanying biopolymer provides an accessible route to developing high-performing reinforced materials absent of petrochemicals.

Further studies and material development can be implemented to investigate the chemical and physical properties of these materials in more depth. These studies will allow for the expansion of non-toxic and high viscosity biomaterials for packaging applications that utilise green chemistry additives, alongside providing biodegradable protective or encapsulating coatings for textile fibres.

1 *An intermediate technical process by which the yarn, fabric or textile is protected by a resin or adhesive*

Key points about bio-based materials raised during development:

- Co-polymerisation was utilised during the material development in order to achieve enhanced tunable structural and mechanical properties based on variations in the component ingredient.
- Due to the water soluble nature of Methylcellulose, it has been utilised in these formulations as an accessible route to material making to demonstrate the versatility of cellulose and its derivatives in forming biofilms with a broad range of properties for packaging and textile applications. Furthermore, methylcellulose is currently exploited in the textile industry for sizing applications, protecting fibres from water and oil. protecting fibres from water and oil solutions. (Tan et al., 2019).

VI. SCALING UP PRODUCTION

As an overview, according to the Regenerative Scaling framework (Garmulewicz et al., 2021) there are three main concepts to consider if we are to sustainably scale up the production of biomaterials from a laboratory to the market.

- DISTRIBUTE: supply, production, and consumption are co-located geographically. This concept means a more regionalized approach to fabrication and the servicing of consumer demand.
- DIVERSIFY: Enable the use of diverse species as well as waste, residuals and byproducts, and practice cultivation and harvesting methods that nurture biodiversity.
- RECIRCULATE: Ensure that the value created is recirculated to support ecoregional communities, supply network partners, and ecosystem services.

Two key enablers of this concept indicated by the Regenerative Scaling Framework (Garmulewicz et al., 2021) are **polycentric governance** and **digital fabrication.** On the one hand, polycentric governments promote **distributed** and **diversified** models by encouraging diversification of stakeholders and promoting local authority better suited to understanding specific ecoregions' possibilities and needs. Also, it considers the needs of communities at the base of the value chain to enable the **recirculation** of value.

Digital manufacturing technologies allow flexible production and **distributive** sourcing of resources at the ecoregional scaling. This same flexibility enables the understanding of local **biodiversity** through smart sensing technology. In addition, it could potentially support transparency and traceability of the value chain to allow recirculation and proper regulation from local governance.

Examples:

Polycentric governance: using the data generated by the Reflow project, municipalities use city-level data of organic waste resources, together with national and global datasets, to offer detailed information for prospective entrepreneurs to develop regional supply chains.

Digital manufacturing: Materiom & SuperLabs platform: Using AI and robotics to radically accelerate materials development and optimization, creating formulations that could be adapted to alternative supply sources.

VI. END OF LIFE STRATEGIES FOR BIO-BASED MATERIALS

A. Collecting bio-based materials

One of today's main constraints for collecting materials in the technical and biological cycles is the **lack of comprehensive legislation** that defines and labels them correctly, supported by standard identification through tools like life-cycle assessment. Currently, no EU legislation addresses the issue. As mentioned before, **labels for biomaterials are heterogeneous and don't consider the difference between countries and their recycling or composting reality** (Rosenboom et al., 2022). Also, different industries have different material flows, which makes it complex to legislate just for bio-based materials.

One opportunity is the **EU circular economy plan (2020)** - part of the European Green Deal - through which a public consultation regarding the "Policy framework on biobased, biodegradable and compostable plastics" is taking place. Besides these future regulations, there is also a necessary financial incentive to compete with the fossil-based material industry (Rosenboom et al., 2022). In addition, another opportunity arises from **Extended Producer Responsibility policies**, where industry and brands are accountable for the products they create.

B. From the end of the life cycle to use-cycle

As mentioned in the Circular Textile Booklet, there are several ways to extend the use cycle of textile products. While we have found that many biomaterials are biodegradable, and once their cycle is over, they can reintegrate their nutrients back into the ecosystem, it is also necessary to explore how to extend their life cycle before biodegradation occurs.

Biomaterials can be recycled **mechanically** or **chemically** (Rosenboom et al., 2022). The first one is the most integrated strategy in our current production systems, but due to mixed compositions tends to cause "downcycling" as each element cannot be separated. Nevertheless, more simple designs and processes could enhance the recyclability strategy. **Chemical recycling** has the potential to degrade biomaterials into monomeric subunits, which can be recycled to remake biopolymers for high-performance biomaterials. However, this technology is still exploratory and expensive, and further development is needed to be widely integrated into the market.

As part of the biomaterials narrative, their ability to be **biodegraded through composting** is generally mentioned. As mentioned above, this capacity is highly dependent on the chemical bonds of the material and its components, which may - or may not - biodegrade when in specific contexts and the presence of microorganisms. While this is a viable option, it becomes complex to scale up as there are few specialised facilities in this area, which often only accept resources that degrade within 6 to 8 weeks. According to Rosenboom et al. (2022), a fourth option for biomaterials is **biological recycling.** This strategy is similar to chemical recycling but aims to break down materials into monomers instead of CO2, which can be used to create biomaterials. However, similarly to chemical recycling, it is still in development.

Finally, **anaerobic digestion** is also a possible way to lower the impact of a biomaterial at the end of life. Biomaterials are decomposed into carbon dioxide and water through this strategy, potentially recovering the heat and energy released.

VIII. OVERALL SUPPLY CHAIN

An essential tool to analyse the total impact of bio-based versus technical materials is **Life Cycle Assessment (LCA).** This approach can help to define the implications of biomaterials production from a cradle to cradle approach, considering items like sourcing, biomass availability and end-of-life strategies.

The sustainability of any material - bio-based or technical - depends heavily on the context and manner of production, so it is vital to conduct an LCA to obtain a systemic view of potential impacts (Rosenboom et al., 2022). For instance, it is key to rely on second and third-generation biomass sources, which do not compete with food crops. Also, the length of a material's useful life must be aligned with its application and its potential reuse or biodegradability strategy. Furthermore, this may vary from country to country due to the different realities of the production industry.

The energy source is also vital to analyse, being more valuable from a sustainable perspective to use **renewable energy sources that match the context of macro ecoregions**. Finally, in the context of a circular economy, it is also essential to include **social implications** and how regenerative the new production system is from a social perspective.

IX. CONCLUSION

Biomaterials have been recognised as a highly valuable option within the emerging circular economy, partly due to their connection as an option to work towards the SDG goals. This has led to brands and consumers looking for bio-based options in the market, but there is a clear trend of biomaterials increasing at the market level.

In this context, it is essential to develop biomaterials considering their entire life cycle and the implications of each stage. In this sense, a tool such as Life Cycle Assessment seems to be key to analysing and developing biomaterials within a curricular and regenerative logic, which is sensitive to its context and considers not only the materiality to work with, but also the energetic and social demand of these new models.

Several opportunities are identified throughout their life cycles, such as using secondary-generation biomass sources like unavoidable food waste from cities and the use of novel production technologies that align with the same chemical principles of our ecosystem. Moreover, the biomaterial systems developed with UFW during the Reflow project exhibit properties and characteristics associated with textile applications, potentially replacing the role of some petrochemical plastics that are complex to recycle or reuse. However, one of the significant challenges is the scale-up of the production of these materials. In this sense, it is key to look to nature to understand and replicate sustainable methods of larger-scale production. Therefore, it is vital to imitate natural production criteria such as distribution, diversification and recirculation. To do this, key tools for this are polycentric governance models and the application of distributed digital manufacturing. In addition, to address the end of life of these materials, various recycling and biodegradation methods are being developed that can facilitate the reuse of biomaterials while maintaining the properties needed by the market.

Finally, while there are many areas to develop further, policies such as the Extended Producer Responsibility and the EU circular economy plan are essential to generate positive incentives for the sustainable development of bio-based materials and textiles.

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XI. APPENDIX

APPENDIX 1 - Mechanical Testing of Biomaterial Systems

The mechanical properties of each biomaterial prototype were assessed using a commercial tensile testing machine. Each material formulation is represented by a unique identification number to differentiate between variations in ingredient concentration within a material system, defined by a common set of ingredients and process steps. The Design of Experiment (DoE) approach to material synthesis facilitates the tuning of material properties required for a desired final application. The initial mechanical properties achieved show promise for application in packaging and textiles.

The data also indicates that with increased concentration of each ingredient component, there is an increase in performance in the strength of the samples. The strength and toughness of a material is defined by the following key factors: strength (hardness) signifies a material's resistance to irreversible deformation, (which is certainly true for ductile materials). However, toughness is defined by a material's resistance to fracture and is therefore assessed as the energy required to cause fracture to a material (Ritchie, 2011).

Notably, samples Methyl-cellulose-Gelatin 2.8 and Methylcellulose-Starch 3.1 show significant strength and toughness, complying with previously reported analogous systems for cellulose and and polysaccharide or amino acid polymerisations (Marichelvam et al., 2019; Yaradoddi, 2020), with 2.8 the strongest and 3.1 the toughest. This may be attributed to the specific types of biopolymers interacting within the structural matrix, depending on the threshold of polysaccharides derived or protein derived material within the system. The degree of plasticiser also influences the interaction between the bonds thus the degree of flexibility which in turn influences the mechanical performance. Thus, by employing a Design of Experiments (DoE) model to the material development of each sample system we are able to derive an optimum performing biomaterial (see Appendix 1). Table 6, indicates the degree at which concentration variations within each component of the material system impacts the mechanical properties for each sample.

Table 4 - Biomaterial Design of Experiment

Co-biopolymers	Unique ID	Elongation at yield (%)	Max force (N)	Ultimate tensile stress (MPa)	Elongation at break (%)	Young's modulus (MPa)
Chitosan & M-Cellulose	1.1	2.39%	72.8	30.42	33.8%	489
	1.6	-	44.3	8.26	12.2%	-
	1.8	2.66%	74.4	15.75	24.3%	247
Gelatin & M-Cellulose	2.1	3.33%	76.6	32.11	14.8%	944
	2.6	2.71%	114.8	26.29	54.4%	372
	2.8	2.88%	133.5	33.82	9.6%	1092
Starch & M-Cellulose	3.1	2.27%	62.2	37.54	41.6%	772
	3.6	1.99%	88.0	24.65	42.3%	522
	3.8	2.21%	67.3	21.02	40.1%	453

Table 5 - Materials Ultimate tensile stress (MPa) Comparison

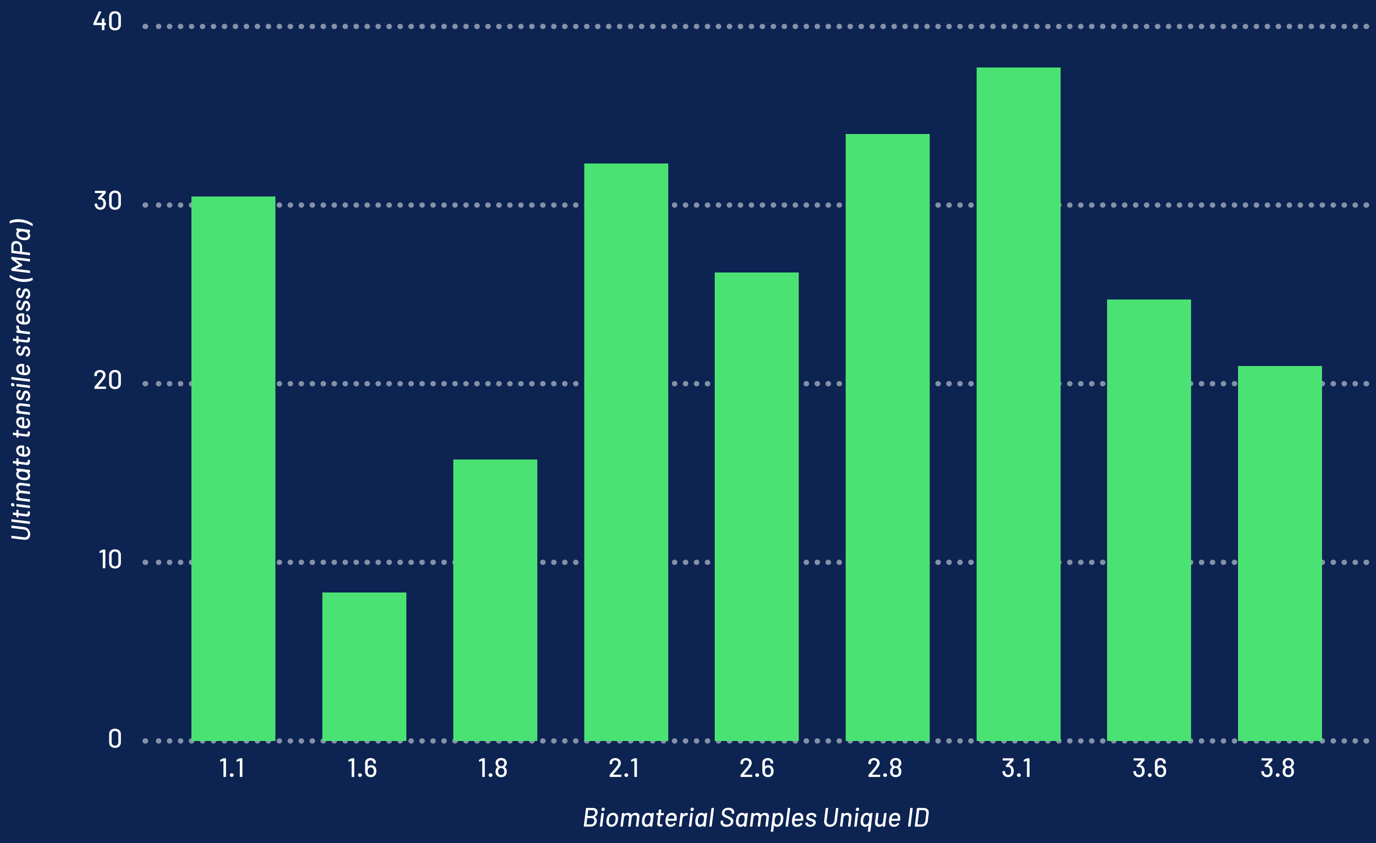
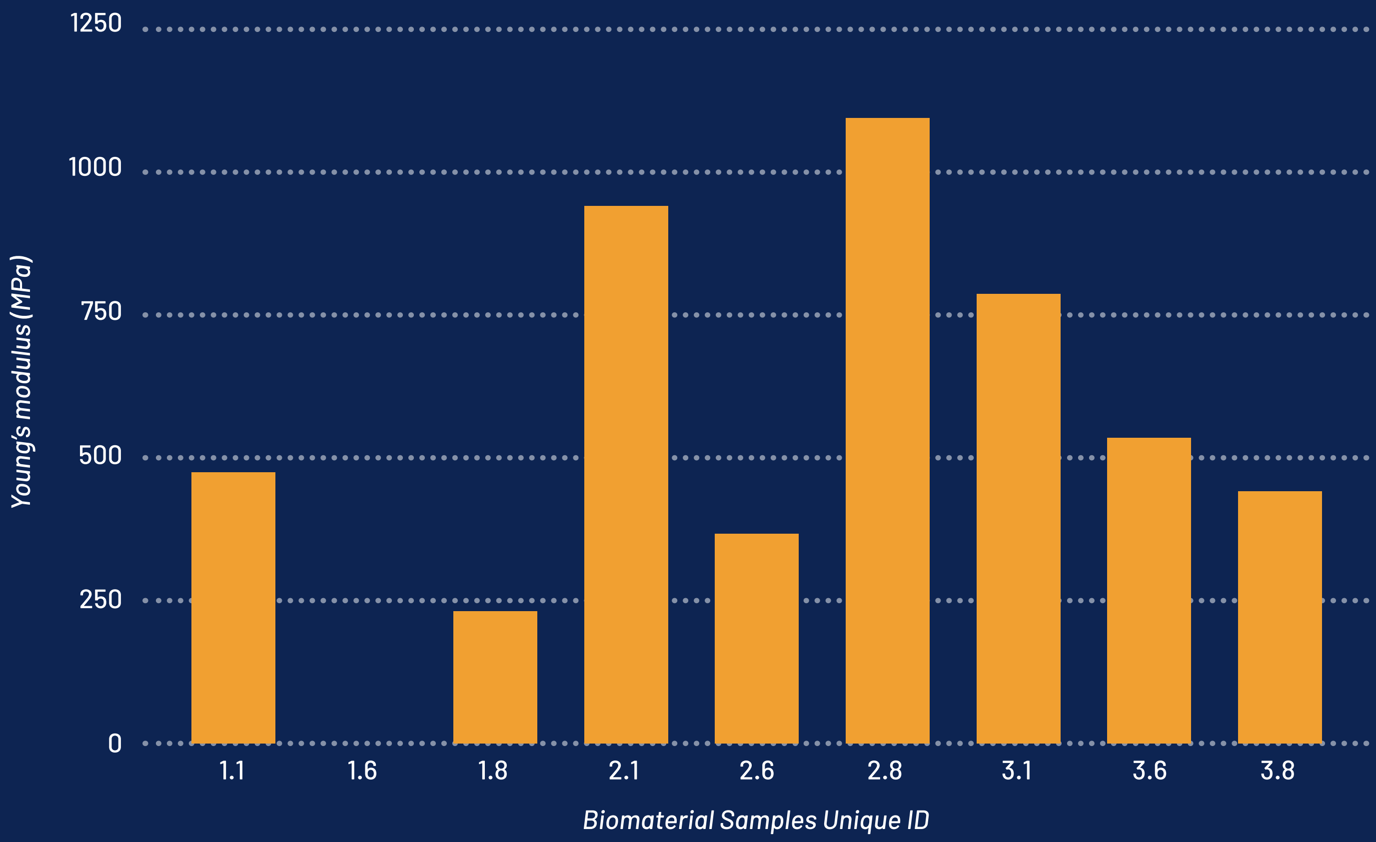


Table 6 - Materials Ultimate tensile stress (MPa) Comparison



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