Xampla

January 2022

Plant Proteins

The Next Generation of Biodegradable Materials

Contents

Executive Summary

At least 8 million metric tonnes of macroplastic waste reaches our oceans every year, where it can slowly degrade into harmful microplastics (Jambeck et al., 2015). An additional 1.5 million metric tonnes of pre-existing microplastics also reach our oceans annually, originating from products containing intentionally added microplastics (IUCN, 2017). Bio-based polymers remove primary production reliance on non-renewable fossil fuel sources, but only about one quarter of the commercially available bio-based plastics are biodegradable (Nova Institute, 2019). Furthermore, many biodegradable polymers (such as polylactic acid) only break down in industrial-composting conditions (temperatures > 58°C for 180 days; ISO 17088). When industrially compostable polymers like polylactic acid reach the oceans, they still break down to produce harmful microplastics (Auta, Emenike, and Fauziah, 2017).

Consequently, scientists across the world continue to search for new bio-materials that can offer the performance of plastics in use (low cost, manufacturable, lightweight, water resistant, durable), but with improved end-of-life properties (safely biodegrading in the environment within weeks).

Plant proteins are recognised as an attractive biomass-derived feedstock, since they are readily available (low cost), renewable, and biodegradable (Shi and Dumont, 2014). However, to date their commercial application has been limited by processing challenges associated with their poor solubility in water (Aghanouri and Sun, 2015).

Xampla spun out from the University of Cambridge to exploit a highly promising and patented new class of structured protein materials, Supramolecular Engineered Protein (SEP). SEP is produced from plants, through a scalable, reproducible, and green manufacturing process that overcomes the solubility limitation of plant proteins, enabling production of materials with highly controlled properties through molecular self-assembly. In use, SEP offers unusually high strength (even comparable to some petroleum-based polymers such as low-density polyethylene) and excellent oxygen barrier properties (comparable to polyvinyl chloride), while at end of life, SEP will safely biodegrade, even if it reaches the oceans.

In this white paper, we describe SEP in detail and explain how our technology is differentiated within the expanding field of bio-based and biodegradable materials.

Amongst the first-developed bio-based and biodegradable materials, cellulose-based materials offer market-leading mechanical properties (tensile strength, flexibility); however, cellulose production is a highly polluting and freshwater-intensive process. Alternative polysaccharide-based materials such as starch or alginate typically have poorer mechanical properties and often require chemical modification, which may have a detrimental impact on biodegradability. In contrast, the unique structure of SEP delivers high strength and flexibility, without requiring any chemical modification.

Amongst next-generation bio-based and biodegradable materials (including polymers produced by microorganisms or genetically modified bacteria such as silk polypeptides and polyhydroxybutyrate), SEP is the only material that is produced from an abundant and sustainably derived raw material, which means that it is the first high-performance bio-based and biodegradable material that can be produced at scale, capable of meeting high-volume commercial application requirements.

Our mission is to reduce marine plastic pollution. SEP is a platform technology that is suitable for replacing petroleum-based and non-biodegradable materials, from the highly visible single-use plastics such as food packaging, to the hidden plastics such as intentionally added microplastics found in personal and homecare products.

The opportunity and challenge of bio-based and biodegradable materials

Opportunity

The global plastic packaging industry (valued at $348BN in 2020; Grand View Research, 2021) is under significant governmental, public, and environmental pressure to implement sustainable alternatives. In the EU, the 'Single-Use Plastics Directive' banned certain single-use plastics in 2021 (Directive (EU) 2019/904), while certain intentionally added microplastics are expected to be banned by 2027 (subject to EU parliamentary approval; ECHA, 2020).

The global bioplastics and biopolymers market is expected to grow from $10.7BN (2021) at a CAGR of 22.7% to reach $29.7BN in 2026 (MarketsandMarkets, 2021). There is a recognised need to move away from the existing linear plastics economy (take-make-dispose) towards a circular packaging economy that maximises value and minimises waste (Ellen MacArthur Foundation, 2017). The UK has an ambition to become a world leader in sustainable packaging and over 40 companies (responsible for over 80% of plastic packaging sold through UK supermarkets) have committed to ambitious 2025 targets as signatories of the UK Plastics Pact (WRAP, 2019).

UK Plastics Pact 2025 Targets (WRAP, 2019)

By 2025

100%

of plastic packaging to be reusable, recyclable or compostable.

By 2025

70%

of plastic packaging effectively recycled or composted

By 2025

ELIMINATE SINGLE-USE PACKAGING

Take action to eliminate problematic or unnecessary single-use packaging items through redesign, innovation or alternative (reuse) delivery models.

By 2025

30%

average recycled content across all plastic packaging

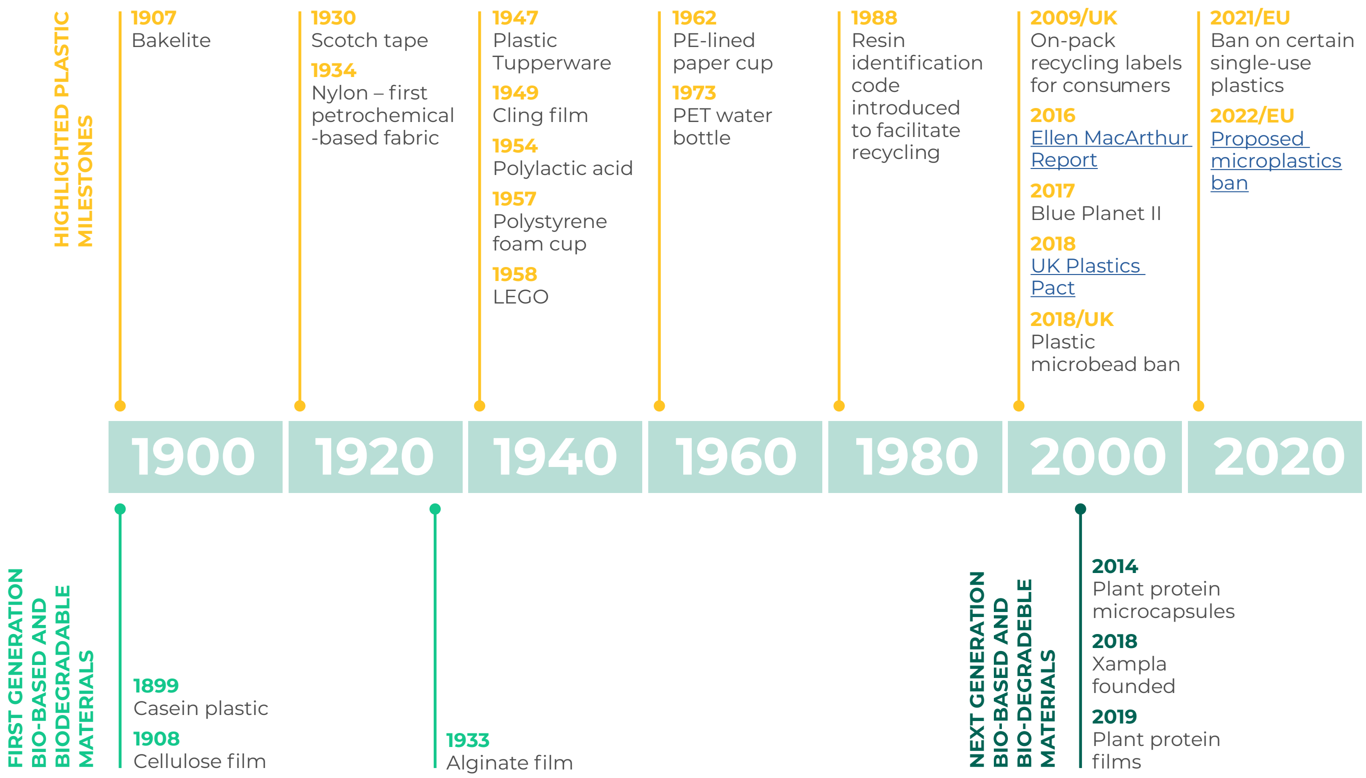
Challenge

Scientists in FMCG companies have been searching for years for bio-based and biodegradable materials to replace conventional plastic packaging and have already tested and trialled multiple pre-commercial/commercial solutions. However, their search for an ideal bio-based and biodegradable material to replace conventional plastic packaging materials has remained limited by three key factors:

1. Poorer performance.
Ultimately, readily biodegradable and home-compostable first-generation bio-based materials (typically based on polysaccharides) have not yet been shown to deliver the required mechanical performance in use (Ramos et al., 2016). Other, less readily biodegradable materials (such as polylactic acid) offer improved mechanical properties, but will only biodegrade under high-temperature industrial-composting conditions (ISO 17088), and still break down in the environment to produce microplastics (Auta, Emenike, and Fauziah, 2017).

2. Higher price/lack of scalable production processes.
Bio-based and biodegradable polymers are typically at least 2-3 times more expensive to produce than petroleum-based polymers, which limits their ability to replace plastics in mass market applications. Next-generation materials such as polymers produced by microorganisms or genetically modified bacteria (silk polypeptides; polyhydroxybutyrate, PHB) offer promising performance, but are challenging to manufacture at scale and are not yet suitable for high volume applications.

3. Lack of materials that go beyond biodegradability, to "do no harm" in the environment.
According to a recent study examining the environmental fate of so-called biodegradable polymers (Narancic et al., 2018) and published examination of TÜV Austria's database (Ghosh and Jones, 2021), only two tested natural polymers to date have been proven to biodegrade under all standard tests of environmental conditions (i.e., spanning soil, freshwater, and marine): PHB and thermoplastic starch. However, both PHB and TPS suffer from poor mechanical performance (they are highly brittle), which limits their commercial application. Incomplete biodegradation of PHB is also harmful to aquatic organisms (González-Pleiter et al., 2019).



Inspired by nature, Xampla has developed a next-generation bio-based and biodegradable material produced from plant proteins. The unique structure of our material has enabled us to overcome the poor performance challenge associated with first-generation bio-based and biodegradable materials. At the same time, our reliance on abundant (low-cost) plant proteins combined with a scalable and non-polluting manufacturing process means that we are able to overcome the high price and production challenges associated with next-generation bio-based and biodegradable materials.

Nature's solution: proteins

Proteins are nature's building blocks and an ideal feedstock for bio-based and biodegradable materials. Proteins have a unique structure, which facilitates a wide range of functional properties, including high mechanical strength as a result of the high intermolecular binding potential between protein chains (Coltelli et al., 2016). Yet, since this high strength is a result of non-covalent rather than covalent bonds, protein-based materials readily biodegrade in the environment, and are even home-compostable.

A reminder on covalent and non-covalent chemical bonding

Covalent bond: When two atoms share one or more electron pairs. Covalent bonds are the strongest types of bonds and define molecular structure. Typical carbon-carbon bond strength: 346 kJ/mol.

Non-covalent bond: Does not involve electron sharing. Instead, non-covalent bonds are formed by a range of different interactions either between molecules or within a molecule. Non-covalent bonds are much weaker than covalent bonds (typical bond strengths < 20 kJ/mol). Despite their individually weak bond strengths, non-covalent bonds play an extremely important role in molecular self-assembly and are responsible for the three-dimensional structure of proteins. Some important non-covalent bonds are hydrogen bonds, ionic bonds, dipole-dipole interactions, van der Waals forces, and hydrophobic interactions.

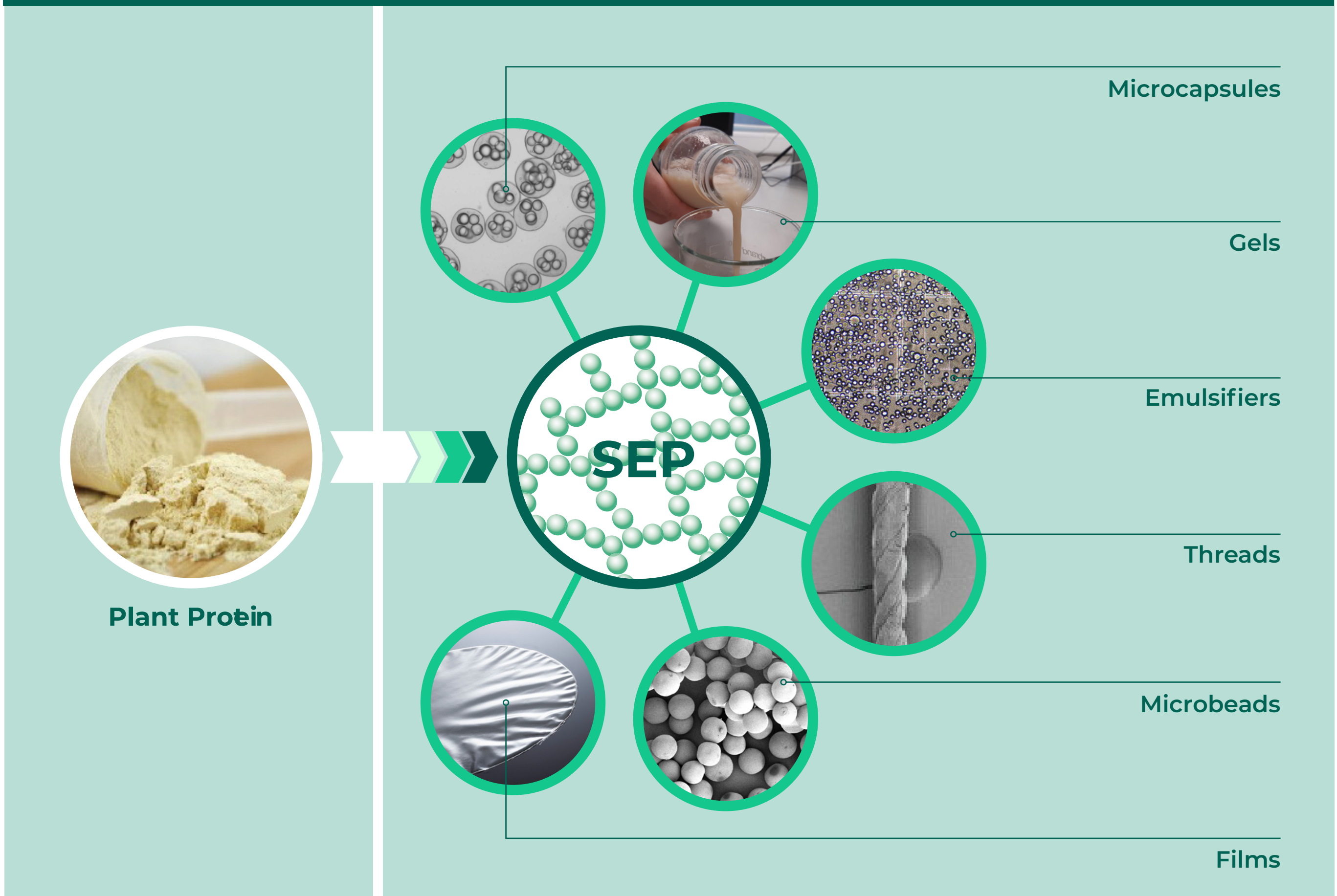
Animal proteins such as gelatin are smaller, more hydrophilic, and easier to process than plant proteins (Martins et al., 2018). However, their hydrophilicity means that water resistance of animal protein-based materials is a challenge (Ramos et al., 2016). In addition, animal proteins are becoming increasingly unpopular with consumers, for cultural, religious, and environmental reasons (Plante et al., 2019).

Plant proteins are an attractive alternative to animal proteins; however, their larger size and higher degree of hydrophobicity makes them much more challenging to process; thus, their commercial application has been relatively limited to date (Aghanouri and Sun, 2015).

Our solution: Supramolecular Engineered Protein

We have developed a scalable, reproducible, and green manufacturing process that overcomes the solubility limitation of plant proteins. By exploiting the natural ability of plant proteins to self-assemble, we have developed a new class of structured protein materials, Supramolecular Engineered Protein (SEP). SEP materials have remarkable functional properties, including high strength and excellent oxygen barrier properties, making them ideal for replacing single-use plastics and microplastics in multiple commercial applications. Through precisely controlling the self-assembly process, SEP can be used to produce gels, microcapsules, emulsifiers, threads, films, and microbeads from a range of sustainably sourced, abundant, and low-cost plant proteins.

From Plant Protein to Supramolecular Engineered Protein (SEP)



Potential impact of our solution

SEP is the first high-performance bio-based and biodegradable material that can be sustainably produced at scale, suitable for high-volume commercial applications. Replacing petroleum-based materials with SEP will:

- Reduce environmental and marine pollution from plastics/microplastics
- Reduce reliance on non-renewable fossil fuel sources
- Reduce greenhouse gas emissions, mitigating climate change
- Support manufacturers across multiple industries to continue to deliver high-performance materials to their customers, while meeting their sustainability goals, and overcoming incoming regulatory hurdles

Xampla's Supramolecular Engineered Protein material

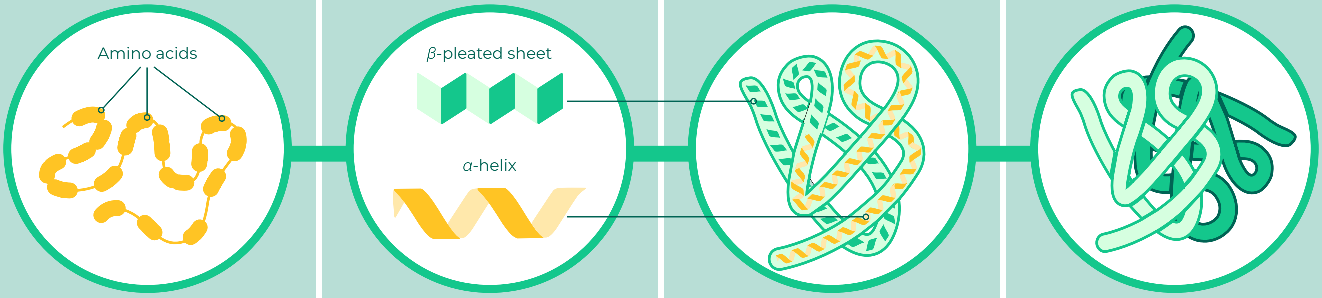
Our technology is based on 15+ years of fundamental protein research led by Professor Tuomas Knowles, a global leader in protein biophysics and Professor of Physical Chemistry and Biophysics at the University of Cambridge. Our patented production process (Kamada et al., 2021) enables scalable, reliable, and reproducible production of gels, microcapsules, films, and resins from a range of abundant plant proteins. Typically, we use widely available high-purity (c80%) food-grade pea protein isolate to produce SEP, but we are also exploring the potential for valorising proteins from plant-based waste agricultural biomass sources, such as leguminous crop residues. Our production process relies on protein's natural ability to self-assemble; thus, only requiring mild processing conditions. Importantly, we do not need to add any chemical modifiers such as cross-linkers, meaning that while SEP is remarkably high strength, it is also readily biodegradable (even home-compostable), and will safely break down in the environment.

Protein self-assembly

Proteins are the building blocks of life. Their unique ability to spontaneously self-assemble into complex structures plays a vital role in most biological processes. Protein self-assembly into β-sheet rich structures is responsible for the remarkable physical properties of silk, which has been described as the "ultimate biomaterial", combining tensile strength with extensibility, and extreme toughness (Rising and Johansson, 2015).

A reminder on protein structure

Primary Protein Structure:	Secondary Protein Structure:	Tertiary Protein Structure:	Quaternary Protein Structure:



Primary Protein Structure:	Secondary Protein Structure:	Tertiary Protein Structure:	Quaternary Protein Structure:
Primary structure: Linear sequence of amino acids in a polypeptide chain, joined together by covalent peptide bonds.	**Secondary structure:** Local folded structures that form spontaneously within a polypeptide as a result of hydrogen bonds between amide hydrogens and carbonyl oxygens found on the peptide backbone. The most common secondary structures are α-helices and β-sheets. Both α-helices and β-sheets are stabilised through hydrogen bonding. β-sheets are additionally stabilised by hydrophobic interactions between hydrophobic side chains.	**Tertiary structure:** Overall 3D structure of a protein, which is determined by weak, non-covalent interactions between the side chains of the amino acids. These interactions include hydrogen bonding, ionic bonding, dipole-dipole interactions, and van der Waals forces. Non-polar, hydrophobic side chains may also cluster through hydrophobic interactions to create hydrophobic regions within the overall protein structure.	**Quaternary structure:** If a protein contains multiple polypeptide chains (subunits), the weak, non-covalent interactions that are responsible for the tertiary structure of a protein will also combine to hold two or more subunits together.

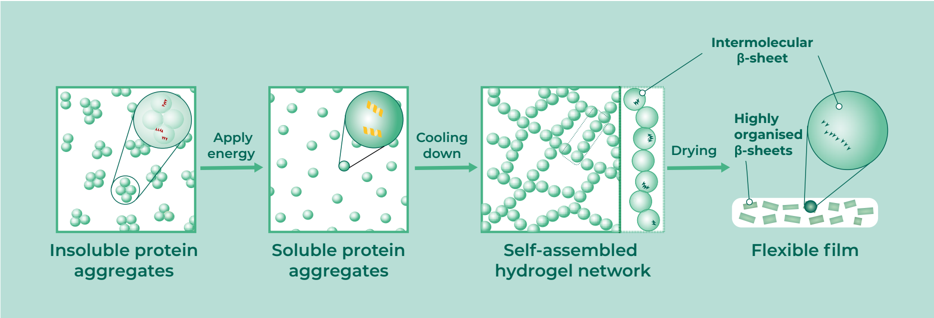
Supramolecular Engineered Protein (SEP)

We have developed a novel method to produce a range of SEP materials from plant proteins, including pea protein. You can view a short video of our technology here.

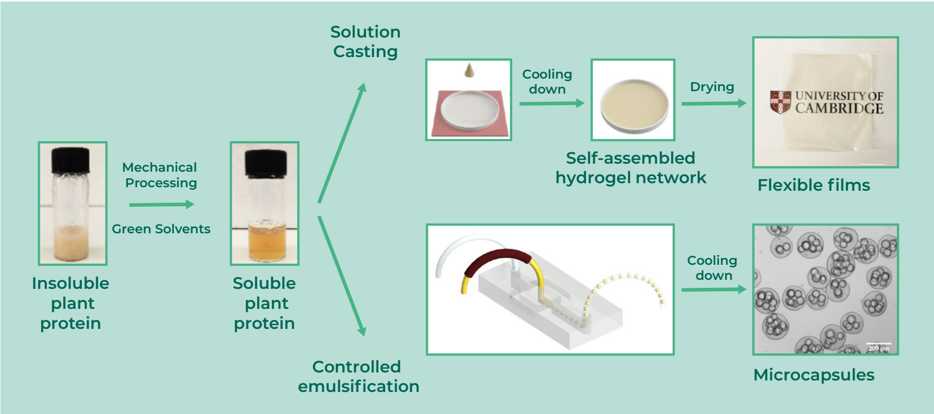
Field peas have a relatively high protein content, ranging from 23-31%, depending on variety, harvest time, and growing conditions (Lam et al., 2016). Pea protein is dominated by salt-soluble/water-insoluble globulins (70-80% of total protein content; high molecular mass of > 150 kDa), with a relatively low content of water-soluble albumins (10-20% of total protein content; low molecular mass of 5-80 kDa; Lam et al., 2016).

Our new approach, which is described in our *Nature Communications* article (Kamada et al., 2021), exploits the use of binary mixtures of green solvents that can dissolve accessible plant protein feedstocks at concentrations as high as 15% (w/v), without requiring further purification processes, and overcoming the current solubility limitation of plant proteins.

The water-insoluble plant proteins form a stabilised colloidal dispersion in binary mixtures of green solvents. Through mechanical processing, we reduce the size of the protein aggregates to increase their solubility. Then, the dispersion is heated above the sol-gel transition temperature (around 90°C) to fully dissolve and denature the plant proteins, without requiring purification or aggressive chemicals. Protein unfolding exposes the previously buried hydrophobic side chains.

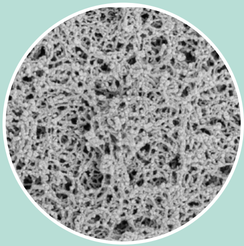


By lowering the temperature of the protein solution in a controlled manner, we create new intermolecular interactions between the proteins, including hydrogen bonds and hydrophobic interactions between the newly exposed hydrophobic side chains. Thus, the proteins self-aggregate to form a hydrogel network composed of fine-stranded aggregates. This hydrogel is stable and can be stored at room temperature, prior to structuring into defined shapes to form self-assembled microcapsules or films (Kamada et al., 2021).

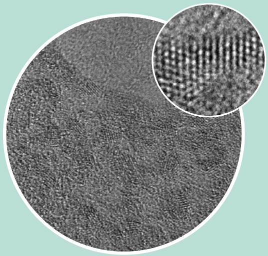


Our production process delivers self-assembled films with superior mechanical properties than plant-protein films generated through conventional methods, and even comparable to films of some synthetic polymers such as low-density polyethylene. The β-sheet rich structure that we have obtained in our film is characteristic of silk materials and is the first time that such high amounts of organised intermolecular β-sheet structures have been reported in plant protein materials (Kamada et al., 2021).

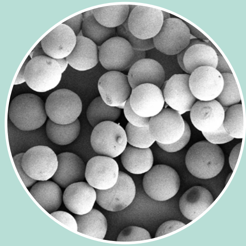
Self-assembled protein hydrogel network



Dried film β-sheet structure



Microcapsules



The highly organised intermolecular β-sheet structure confers not just mechanical strength, but also excellent oxygen barrier properties (comparable to polyvinyl chloride). At the same time, since the proteins are stabilised through intermolecular bonding rather than chemically cross-linked, SEP materials readily biodegrade, even when released into the environment.

Polyamides: Remarkably strong and elastic materials

Silk: Primary structure consists of a non-repetitive globular N-terminal domain, followed by a linear repetitive sequence of amino acids (predominantly alanine and glycine), followed by a non-repetitive globular C-terminal domain (Rising and Johansson, 2015). Silk proteins self-assembly into β-sheet crystals. Described as the “ultimate biomaterial”, silk combines high tensile strength with extensibility, and extreme toughness (Rising and Johansson, 2015).

Nylon: First petrochemical-based fabric, invented in 1934. Nylon offers many of silk’s properties (high strength, flexibility) but can be manufactured at scale. However, virgin nylon is produced from non-renewable fossil fuels in an energy-intensive process. Nylon is neither biodegradable nor widely recycled, meaning it typically ends up as landfill waste or is incinerated. In the oceans, nylon breaks down to produce harmful microplastics.

Xampla’s SEP: Combines the structural properties of silk (β-sheet structures) with the scalable manufacturing capability of nylon. At the same time, unlike nylon, our bio-based and biodegradable SEP material is produced from an abundant (low-cost) and renewable raw material, using a mild and non-polluting process. At end-of-life, SEP safely and readily biodegrades, even if it reaches the oceans.

By varying the processing conditions, our novel approach enables scalable, reliable, and reproducible production of a range of plant-based materials with highly controlled properties. In addition to its excellent material properties, SEP is:

(i) Produced from abundant, renewable, and bio-based plant protein feedstock. Ensuring security of supply when integrated into high volume supply chains.

(ii) Produced from food-grade raw material with food-safe processing route, creating new market opportunities in edible applications including films and coatings.

(iii)Biodegradable in home-composting conditions, as well as in marine, soil, and freshwater environments according to industry standards. SEP exceeds the performance requirements of existing biodegradability standards, which assess biodegradability in terms of carbon dioxide release but do not consider ecotoxicity or release of potentially harmful breakdown products. SEP breaks down safely in the environment, without releasing any ecotoxic or harmful components that could be produced during partial or complete biodegradation.

Food versus material?

The use of a food-grade feedstock to produce bio-based materials creates a debate around the use of agricultural land to produce materials rather than food. For edible applications, the feedstock must be food-grade; however, for non-edible applications, we are exploring alternative plant protein feedstocks, including producing SEP from waste plant-based agricultural biomass. Globally, agriculture generates 140 billion tonnes/year of biomass waste, which is equivalent in terms of energy and raw materials to c50 billion tonnes of crude oil (UNEP, 2009). For example, during the UK pea crop harvest, large amounts of crop residues are ploughed back into the soil to increase the organic matter content, acting as a natural fertiliser. However, interest is growing in the potential to valorise leguminous crop residues not needed to fertilise the soil by extracting nutrients including proteins (Tassoni et al., 2020).

What does biodegradable mean?

- **Industrially compostable (ISO 17088; EN 13432):** Material will biodegrade under industrial-composting facilities (less than 10% of original material remains after industrial-composting at temperatures above 58°C for 180 days).
- **TUV Vinçotte OK Compost Home:** Material will biodegrade under home-composting conditions (less than 10% of original material remains after home-composting at ambient temperature – between 20 and 30°C - for 365 days).
- **TUV Vinçotte OK biodegradable MARINE/SOIL/WATER:** Material will biodegrade under ambient conditions in marine/soil/freshwater environments (less than 10% of original material remains after testing at a temperature of between 20 and 25°C for 56 days)

Our IP portfolio

Five patent families protect our core technology:

v(i) WO 2016/034728: Protein capsules. Published 10th March 2016, with a priority date of 4th September 2014. A PDF copy of this patent may be downloaded here. Filed by Cambridge Enterprise Limited and Harvard College; exclusively licensed by Xampla.

(ii) WO 2020/178448: Plant based functional materials. Published 10th September 2020, with a priority date of 7th March 2019. A PDF copy of this patent may be downloaded here. Filed by Cambridge Enterprise Limited; exclusively licensed by Xampla.

(iii) PC 775644GB: Plant-based microcapsules. Filed 8th September 2020 by Cambridge Enterprise Limited and Xampla Limited.

(iv) PC 931489GB: Protein dispersions. Filed 8th September 2020 by Xampla Limited.

(v) PC 932089EP: Plant protein-starch films. Filed 5th November 2021 by Xampla Limited.

We have developed a robust IP management strategy and continue to strengthen our IP portfolio, with further patent filings in progress. Our process development is only disclosed to specific partners under confidentiality agreements and we retain know-how around manufacturing within Xampla.

How does Xampla's material compare to other bio-based and biodegradable materials?

There are three broad categories of bio-based materials (Fera, 2019):

(i) **Polymers derived from bio-based monomers;** notably, polylactic acid derived from corn starch or sugarcane.

(ii) **Polymers produced by microorganisms or genetically modified bacteria;** notably, polyhydroxyalkanoate (PHA) and polyhydroxybutyrate (PHB), including from marine sources, as well as synthetic silk polypeptides

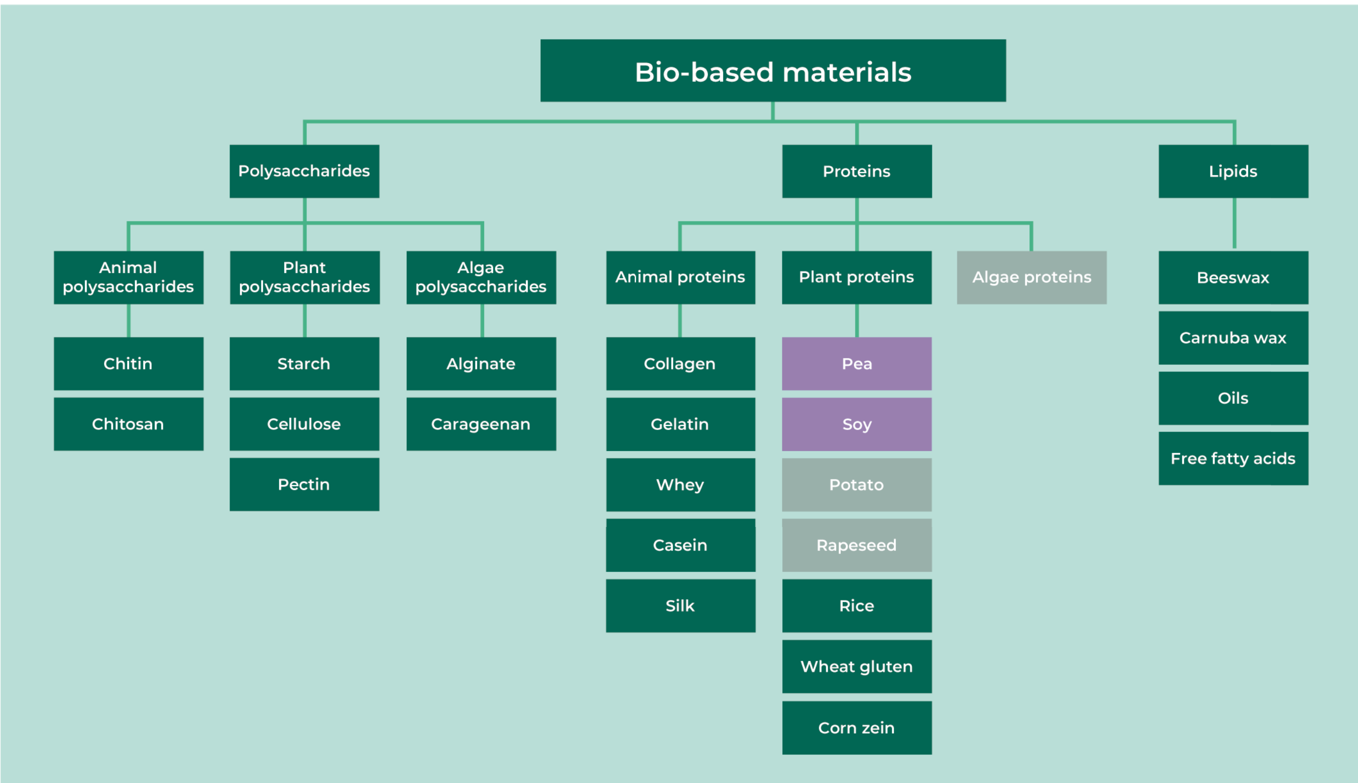
(iii) **Natural polymers directly extracted from biomass:** either polysaccharides, lipids, or proteins.

Polymers derived from bio-based monomers are the most well-established bio-based materials, representing 2% of global polymer production (Nova Institute, 2019). Polylactic acid is designed to substitute petroleum-based plastics such as PET (polyethene terephthalate) and is used for plastic films and food containers.

However, polylactic acid only biodegrades under high-temperature industrial-composting conditions (ISO 17088) and breaks down in the environment to produce microplastics (Auta, Emenike, and Fauziah, 2017).

Next-generation bio-based and biodegradable materials, polymers produced by microorganisms (polyhydroxyalkanoate, polyhydroxybutyrate) or genetically modified bacteria (silk polypeptides) offer tuneable performance, even comparable to some petroleum-based polymers (Follain et al., 2014). However, their commercial application is currently limited by the lack of low-cost and scalable production processes (Kavitha, Rengasamy, and Inbakandan, 2018).

Natural polymers can be directly extracted from a wide range of biomass sources (including waste streams). These bio-based materials can be categorised into polysaccharides, lipids, and proteins (Chen et al., 2019).



Polysaccharides

Cellulose:
Amongst bio-based and biodegradable materials, cellulose-based materials offer market-leading mechanical properties (notably strength and flexibility), with a long history of commercial application (cellophane – a transparent film made from wood cellulose - was patented in 1908). Cellulose is the most abundant biopolymer and can be extracted from wood, cotton, hemp, and other plant-based materials (Cazón et al., 2017). The main drawback of cellulose is its insolubility in water and other polar solvents. The dominant commercial-scale process for dissolving cellulose (known as the viscose process, responsible for c95% of annual production volumes) relies on derivatising cellulose with carbon disulphide to produce cellulose xanthate, which is then dissolved in sodium hydroxide (Hermanutz et al., 2008). This process requires significant volumes of toxic and polluting chemicals, as well as freshwater, although research is ongoing to develop more environmentally friendly processes; for example, using ionic liquids (Hermanutz et al., 2008).

Chitosan:
Derived from deacetylation of chitin, the second most abundant biopolymer after cellulose (Khwaldia, Arab-Tehrany, and Desobry, 2010). Pure chitosan films are highly hydrophilic and lack mechanical robustness, although research is ongoing to improve their mechanical properties and water resistance through cross-linking, such as with citric acid (Nataraj et al., 2018).

Starch:
Starch is a semi-crystalline material, composed predominantly of amylose and amylopectin (Cazón et al., 2017). Compared to petroleum-based polymers, starch materials offer high tensile strength, but limited elongation, meaning that they are highly brittle (Cazón et al., 2017). This brittleness is a consequence of the amorphous regions formed by amylose. Research is ongoing to improve the mechanical properties (brittleness) through the addition of plasticisers (such as glycerol; Santana et al., 2018) and reinforcers (such as cellulose fibres; Fazeli, Florez, and Simão, 2019). Starch is most suitable for packaging dry products; for example, thermoplastic starch foam has found commercial application as biodegradable packaging peanuts to protect fragile goods and home-compostable magazine wrapping is made from potato starch.

Alginate:
Extracted from seaweed and used to produce flexible films, which readily biodegrade in the environment (Khalil et al., 2017). Bonniksen developed and patented an alginate film production method in the 1930s (US2030566A). Since alginate is extracted from seaweed, production does not require land, freshwater, insecticide, or fertilisers (Adams et al., 2017). However, compared to petroleum-based materials, alginate-based materials are generally characterised by poor mechanical properties (limited strength and water vapour barrier properties; Cazón et al., 2017). Research is ongoing to improve these properties through the addition of plasticisers (including glycerol; Santana and Kieckbusch, 2013) and reinforcers (including cellulose fibres; Deepa et al., 2016). However, the poorer mechanical properties and lack of scalable manufacturing processes, combined with the relatively high cost of the raw material (at c$13,000/tonne; CBI, 2018), currently limit alginate-based materials to relatively niche markets such as edible films.

Lipids

Naturally occurring lipids such as fatty acids can be used to provide hydrophobic coatings with excellent water vapour barrier properties (Khwaldia, Arab-Tehrany, and Desobry, 2010). However, lipids generally have poorer oxygen barrier properties and are highly brittle, making them unsuitable as a replacement for petroleum-based plastics in many applications.

Animal proteins

The unique structure of proteins means that protein-based materials deliver improved mechanical properties compared to polysaccharide- (excluding cellulose) and lipid-based materials (Calva-Estrada, Jiménez-Fernández, and Lugo-Cervantes, 2019).

Gelatin:
Derived from collagen, a structural protein that accounts for >30% of the total protein content of most animals (Brigham, 2018). Gelatin is dominated by glycine, proline, and hydroxyproline amino acid residues, and characterised by a low molecular weight of 1.4 – 26 kDa (Brigham, 2018). Consequently, gelatin readily dissolves in water. Although gelatin films and coatings have been proposed as a potential bio-based and biodegradable replacement for plastic food packaging, gelatin films have found limited commercial application to date since they offer poor water resistance (Ramos et al., 2016).

Casein:
Primary protein found in bovine milk and produced as a by-product of the dairy/dairy processing industries (Ryder et al., 2018). Casein-based biomaterials were originally patented in 1899. Casein films with excellent oxygen barrier properties and good mechanical properties can be formed through self-assembly (Calva-Estrada, Jiménez-Fernández, and Lugo-Cervantes, 2019). The main drawback of casein-based materials is their high water vapour permeability. In many commercial applications, casein is limited by its status as an allergen and its unsuitability for vegans or vegetarians.

Silk:
Exhibits exceptional mechanical properties, combining high tensile strength with high extensibility, and extreme toughness as a result of the β-sheet secondary structure. The main challenges for silk-based materials are the lack of commercial-scale production processes, which makes them unsuitable for mass market applications, and their high water vapour permeability (Numata, Ifuku, and Isogai, 2018).

Plant (and algae) proteins

Plant (and algae) proteins are attractive alternatives to animal proteins. In commercial applications, the reliance on plant (and algae) proteins enables manufacturers to deliver on their sustainability/environmental credentials, while relying on an abundant (low-cost) raw material, ensuring security of supply. We can solubilise and process plant proteins into SEP and have developed scalable production processes to convert SEP into useful materials, such as microcapsules and films. These products offer significantly improved mechanical properties compared to unstructured plant protein materials, particularly in terms of increased tensile strength and reduced brittleness (Calva-Estrada, Jiménez-Fernández, and Lugo-Cervantes, 2019).

Compared with hydrophilic animal proteins, hydrophobic plant (and algae) proteins offer improved water vapour barrier resistance, although (in common with other bio-based and biodegradable materials such as cellulose), water vapour permeability remains the main performance limitation of plant protein-based materials (Calva-Estrada, Jiménez-Fernández, and Lugo-Cervantes, 2019). We have found that SEP offers improved water barrier properties compared to unstructured plant protein materials, and that water resistance can be significantly improved by the addition of a small amount (0.5% w/v) of hydrophobic plant protein, such as corn zein.

For edible applications, there are several candidate food-grade plant and algae proteins that could be used to produce SEP:

Soy protein:
Soy is the established market leader in novel alternative protein sources (McKinsey, 2019) and commonly used as a model plant protein in research applications. Although soy is low cost (c$2,000/tonne; McKinsey, 2019), soy production causes deforestation (Brazil is responsible for 37% of global production), local water resource stress, and herbicide overuse (Chain Reaction Research, 2019). Soy is also an allergen (ECARF, 2016). Consequently, we do not use soy protein to produce SEP products.

Pea protein:
Emerging market leader in novel alternative protein sources, recognised for its improved sustainability credentials compared to soy and its non-allergenic status (McKinsey, 2019). To date, our development work has largely focused on the production of SEP from food-grade pea protein isolate (c$3,400/tonne), which has strong potential for UK and EU production (EC, 2018).

Algae proteins:
Similarly to alginate production, proteins extracted from algae are an attractive raw material as they do not require land, freshwater, insecticide, or fertilisers (Adams et al., 2017). However, low-cost and environmentally friendly extraction of algae proteins remains a challenge (Bleakley and Hayes, 2017).

Xampla's feedstock strategy

In the short-term (1-2 years), we will manufacture SEP materials from pea protein isolate. Globally, 140,000 tonnes of pea protein are used in the food ingredient sector, with a protein price per tonne of $3,400. This indicates that the pea protein market can meet our feedstock supply requirements up to 2025 without exceeding 10% market share, with a low price and widely available raw material. However, in the medium-term (3-5 years), since the global pea protein isolate market is limited and its use in material production would eventually compete with food production, to scale SEP production, we will transition from food-grade plant protein isolate to valorisation of waste streams such as surplus leguminous crop residues. This also offers the potential for cost reduction. Protein extraction and purification from agricultural waste streams continues to be an active area of European-led research, with multiple pre-commercial solutions in development (de Schouwer et al., 2019).

We are working with the UK's National Non-Food Crops Centre to identify potential feedstock supply chains. Five key potential feedstocks have been identified. In each case, since transport of waste with high water content (typically over 90%) is costly and would have a significant climate change impact, protein extraction technologies must be technically and economically viable at a single site level.

1. **Faba bean hulls:** UK faba bean and pea crop residues could provide over 100,000 tonnes/year of plant protein feedstock, while across Europe, 3 million tonnes/year of legume waste (LEGUVAL, 2016) could provide 450,000 tonnes/year of plant protein. Our projected 2026 plant protein supply requirements of 15,000 tonnes/year could be met by processing 83,250 tonnes/year of leguminous crop residues, accounting for c20% of European feedstock available. We are engaging with a leading UK producer of faba beans, Frontier Agriculture, who also produce dry faba bean hulls as a byproduct. Faba bean hulls contain 18% (dry matter) protein and are typically either ploughed into the field or sold for animal feed (at around £130/tonne). However, animal feed prices fluctuate and faba bean producers including Frontier Agriculture have expressed interest in a baseload application for dry bean hulls that could stabilise pricing in the supply chain. Frontier Agriculture process 50,000 tonnes/year of faba beans from over 200 farmers at their site in Nottinghamshire, producing 6,000 tonnes/year of faba bean hulls. At laboratory-scale, we have extracted and purified protein from faba bean hulls provided by Frontier Agriculture, following a published isoelectric precipitation and salt extraction process (Karaca, Low, and Nickerson, 2011). Then, we successfully processed faba bean hull protein into SEP, validating performance in a coating application. Working with process engineering consultancy 42 Technology, we have designed a scaled-up process for protein extraction from faba bean hulls based on batch processing in standard 2,000 L vessels, with one batch of 600 kg of faba bean hulls able to produce 38 kg of protein.

2. **Rapeseed cake protein:** Rapeseed cake is a byproduct of rapeseed oil production, which is typically sold for animal feed. It is a major agricultural material; global rapeseed cake production reaches 49 million (dry) tonnes/year, with a protein content of 30-40% (dry matter), potentially providing up to 18 million tonnes of protein (VTT, 2020). We are working with the Fraunhofer Institute, who are producing technofunctional plant proteins, including proteins extracted from rapeseed cake. We have successfully processed rapeseed cake protein into SEP, validating performance in a coating application. Napiferyn Biotech (founded in 2014 in Poland) have reached pilot-scale for protein extraction from rapeseed cake and are commercialising their technology through developing licensing agreements with rapeseed oil producers, who will manufacture protein at commercial scale.

3. **Potato protein:** In north-west Europe, potatoes are widely used to produce starch, for food and industrial markets. This results in large quantities of protein-containing by-products, such as potato juice and waste waters. These soluble fractions only contain around 1-2% (wet matter) protein. However, Europe produces 6 million m^3 of potato juice (Pęksa and Miedzianka, 2021), which could potentially provide up to 90,000 tonnes/year of protein. In the Netherlands, Avebe extract protein from waste potato juice, producing food-grade and feed-grade proteins. In the UK, Branston (a large potato distributor) is collaborating with B-hive Innovations, who have reached pilot-scale potato protein extraction, processing over 40 tonnes of low-value potatoes and potato peels. In April 2021, construction started on the UK's first commercial-scale potato protein extraction factory, at Branston's site in Lincolnshire.

4. **Dried Distillers Grain with Solubles (DDGS):** DDGS is a by-product of brewing and distillery processing of grains, which contains 27-35% protein and is currently used for animal feed. DDGS and wet distillers grain provided 1.48 million tonnes of crude protein for animal feed in the EU in 2020. Edinburgh-based Horizon Proteins (founded in 2014) have developed and patented their process and purification technologies to extract protein from pot ale, a liquid residue from the first distillation step that is primarily treated by land or sea disposal or anaerobic digestion. The Scottish whisky industry produces 2.7 billion litres of pot ale each year, which could provide nearly 36,000 tonnes/year of protein (White et al., 2020). Horizon Proteins have completed three large-scale industrial trials, extracting high-purity (>80%) protein from pot ale for aquaculture feed.

5. **Rubisco:** Rubisco is a soluble protein found in green vegetables and green plant leaves, thought to be the most abundant protein in the world. In 2018, the Cosun Beet Company acquired start-up Green Protein, who have developed a process to extract soluble protein (Rubisco) from sugar beet leaves, opening a demonstration plant in the Netherlands in 2019. The leaves constitute 20-34% of the crop and are typically left on the fields after harvest. Yet, sugar beet leaves contain 12.4% (dry matter) protein content (Starke and Hoffmann, 2014). Globally, 4.5 million ha of sugar beet are harvested, providing 180 million (wet) tonnes of sugar beet leaves (Bruins and Broeze, 2020), which could potentially provide up to 3 million tonnes/year of protein.

In the longer term (5+ years), feedstock supply from gas-to-protein production will eliminate land use and freshwater issues, while potentially even providing a negative CO_2e (carbon dioxide equivalent) process by fixing anthropogenic CO_2e that would otherwise be released into the environment (Pikaar et al., 2018; The Carbon Trust, 2016). These processes can convert waste gases (e.g., captured from power stations, steelworks, or landfill sites) into high-quality single-cell protein (typically, around 70% dry matter protein content), currently targeting the animal feed industry.

Three key companies are:

1. **Deep Branch:** Have developed a containerised, mobile unit, which can be installed on industrial sites close to CO_2 capture sources. Along with clean (low-carbon) hydrogen and ammonia, the captured CO_2 is fed to microbes to produce single-cell protein (Proton™; 70% dry matter protein content) in a continuous fermentation process. Deep Branch are currently at pilot scale, producing tonnes of protein per year for animal feed applications. They are targeting commercial production by 2023, with plans to reach protein production volumes of 100,000 tonnes/year by 2025. One of their key partnerships is with Drax in North Yorkshire, capturing power station CO2 emissions. Compared to animal feed production, the Deep Branch process reduces CO_2e emissions by 90%, with the majority of CO_2e emissions arising from the addition of ammonia to deliver the N content of proteins.

2. **Calysta:** Have developed a methane-to-protein production process relying on fermentation by methanotrophic microorganisms to produce single-cell protein (FeedKind® Protein; 71% dry matter protein content). Calysta currently uses natural gas as their feedstock source, but are also exploring biogas sources (e.g., captured methane released from landfill sites or produce during anaerobic digestion). Analysis by The Carbon Trust indicates that an optimised process relying on biogas, renewable energy, and capturing the carbon dioxide released during the fermentation process as well as exhaust gases from the product drying unit would achieve a negative carbon footprint of –2.790 tonnes of CO_2e per tonne of FeedKind® Protein produced (The Carbon Trust, 2016). Calysta is currently scaling up, producing protein for fish, livestock, and pet food, with plans to begin commercial-scale production at their first facility in China in 2022, initially reaching 20,000 tonnes/year, followed by expansion to 60,000 tonnes/year. They recently secured funding to commission a second commercial-scale plant, outside Asia.

3. **LanzaTech:** Have developed a carbon monoxide-to-ethanol production processes relying on fermentation by bacteria originally found in rabbit droppings. Protein is produced as a coproduct and LanzaTech is already producing and selling tonnes of single-cell protein to the animal feed industry, alongside 46,000 tonnes/year of ethanol produced from waste CO at a steelworks plant in China. Life cycle analysis for ethanol production indicates that CO_2e emissions are reduced by close to 90% compared to petrochemical-derived gasoline production (Handler et al., 2016). By valorising coproducts such as protein, CO_2e emissions are reduced even further, with additional scope to capture the carbon dioxide released in the fermentation process, similarly to in Calysta's production process, potentially unlocking a negative carbon footprint (The Carbon Trust, 2016).

What to look for in a biodegradable material

For manufacturers looking to meet proposed EU single-use plastics (Directive (EU) 2019/904) and intentionally added microplastics bans (ECHA, 2020), as well as the UK's ambitious Plastic Pact 2025 targets (WRAP, 2019), SEP has the potential to offer all the attributes of an ideal bio-based and biodegradable material:

- **Sustainable feedstock,** produced from low-cost, abundant plant-based raw materials, potentially even from waste agricultural biomass sources.
- **Scalable and green manufacturing process,** which can be used to produce a wide range of structured materials, including microcapsules and films.
- **Excellent performance in use**, with unusually high strength and excellent oxygen-barrier properties that can even match that of some petroleum-based polymers.
- **Safe for human consumption**, as well as vegan and allergen free, creating new market opportunities in edible applications such as microencapsulation of unstable micronutrients.
- **Rapid biodegradation** in industrial- and home-composting conditions, as well as in soil and freshwater environments according to industry standards. Marine biodegradation is also anticipated and testing will be completed shortly.

Conclusions

Pressure on manufacturers to transition to sustainable bio-based and biodegradable plastic-free alternatives that continue to deliver performance in use has never been greater.

Inspired by nature, Xampla has developed a next-generation bio-based and biodegradable material produced from widely available and low-cost plant proteins. Combining the structural properties of silk (high degree of organised intermolecular β-sheet structures), with a scalable and non-polluting manufacturing process, SEP is the first bio-based and biodegradable material that can deliver the required mechanical performance in use, while readily and safely breaking down when released into the environment.

SEP can be processed to produce a wide range of structured materials, including microcapsules and films, making it an ideal choice for replacing petroleum-based materials in multiple high-volume commercial applications, ranging from homecare to food and beverages. Our next-generation biodegradable plant protein-based materials can play a leading role in the global transition to a bio-based and circular economy, addressing six UN Sustainable Development Goals: 8 (Decent work and economic growth); 9 (Industry, innovation, and infrastructure); 12 (Responsible consumption and production); 13 (Climate action); 14 (Life below water); and, 15 (Life on land).

To find out more about Xampla and our patented SEP technology, request commercial samples, and discuss development needs, please contact our CEO Simon Hombersley at simon@xampla.com.

We are always looking for new applications where our next generation bio-based and biodegradable material can add value, so please talk to us about how we can help you to meet your specific requirements.

You can also find out more about our technology on our website (www.xampla.com), or follow us on LinkedIn (https://www.linkedin.com/company/xampla/) and Twitter (@XamplaUK).

About Xampla

Xampla is the world leader in natural polymers for commercial applications. Our mission is to reduce marine plastic pollution, replacing everyday single-use plastics such as sachets and flexible packaging films, as well as "hidden" plastics, such as intentionally added microplastics in liquids and lotions.

Xampla spun-out of the University of Cambridge to commercialise Professor Tuomas Knowles' world-leading and patented protein material research. The company is led by serial entrepreneur Simon Hombersley, who has 20 years' experience of founding and scaling successful Green Impact businesses, including as start-up CEO/founder of Lontra and Oxford Flow. CTO Marc Rodriguez Garcia developed the processes and applications that are the basis of Xampla's defensible technology, working with Professor Knowles before co-founding Xampla.

17,000

Xampla's Technical Adviser and cofounder Professor Tuomas Knowles is a global leader in protein biophysics, with 200+ peer-reviewed journal articles cited over 17,000 times. He is a named inventor on 14 patents and was named UK Academic Entrepreneur of the Year by Business Weekly. His research focuses on understanding and controlling the fundamental mechanisms of protein self-assembly processes, creating new types of functional materials. In his role as Professor of Physical Chemistry and Biophysics at the University of Cambridge, he leads a biophysics and biophysical chemistry research team of nearly 40 people. An experienced start-up founder, Professor Tuomas Knowles has cofounded two additional University of Cambridge spin-outs from his world-leading protein research: Wren Therapeutics and Fluidic Analytics.

Certified B Corporation™

We are a Certified B Corporation™, which demonstrates that we balance profit and purpose through applying the highest standards of social and environmental performance, public transparency, and legal accountability.

Building on our patented platform technology, Xampla's bio-based and biodegradable materials are set to replace traditional materials such as plastics/microplastics across multiple global markets, while also supporting the creation of entirely new global markets.

To stay up to date with developments at Xampla, please join our mailing list by sending an email to subscribe@xampla.com.

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