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ALGÆUROPE2020


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ALGAE: AN INNOVATIVE BIOPOLYMER FEEDSTOCK FOR PRODUCING ADVANCED GENERATIONS OF BIOPLASTICS

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Microalgae Processes Platform
CEA Tech en Région Sud
Centre de Cadarache, France

INTRODUCTION

- **Plastic problems:**

  - **Global** production of **plastics** → **322** million tonnes (2015)

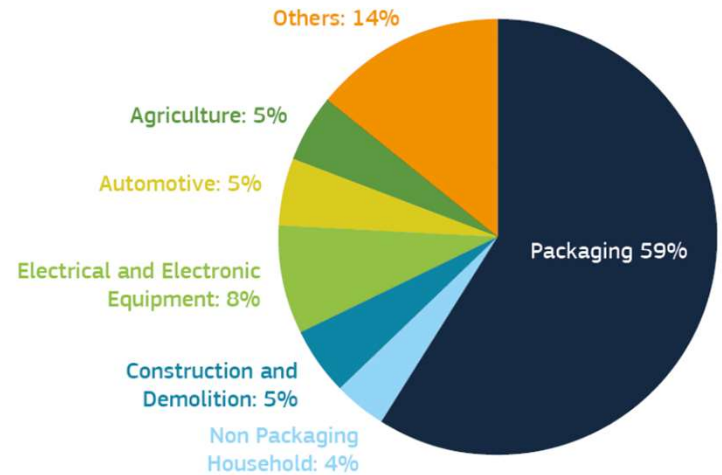
  - **EU Reuse** and **recycling** of end-of-life plastics is **very low**

  - **EU** plastic **waste**: 25.8 million tonnes / year
    - Landfilling 31%
    - Incineration 39%
    - Less than 30% is collected for recycling
      A significant share leaves the EU → third countries
      to be treated with different environmental standards

  - 70 - 105 billion € /year are **lost** to the economy
    after a **very short** first-use **cycle**

- **European Strategy for Plastics in a Circular Economy**
  https://eur-lex.europa.eu/resource.html?uri=cellar:2df5d1d2-fac7-11e7-b8f5-01aa75ed71a1.0001.02/DOC_1&format=PDF

EU PLASTIC WASTE GENERATION IN 2015



Packaging waste EU :
173 kg / year per inhabitant (2017)

LEGAL FRAMEWORK

- **EU waste rules (updated in 2018)**
  - **Landfilling** Directive
    - Landfills should remain **exceptional**
    - **2030**, waste **suitable for recycling** → **not permitted** to be disposed of to landfill
  - **Waste framework** Directive
    - **Biodegradable** and **compostable** packaging will be c**ollected** with the **bio-waste** and **recycled** in **industrial composting** and **anaerobic digestion**
  - **Packaging** and **packaging waste** Directive
    - **Increase** packaging waste **recycling**
    - **Minimise** the environmental **impact**
    - **Reduce** Europe's **dependence** on imported raw materials.
- **The waste package is a key element of the Circular Economy Action Plan**

European Commission

DIRECTIVE (EU) 2018/850 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL
of 30 May 2018
amending Directive 1999/31/EC on the landfill of waste
(Text with EEA relevance)

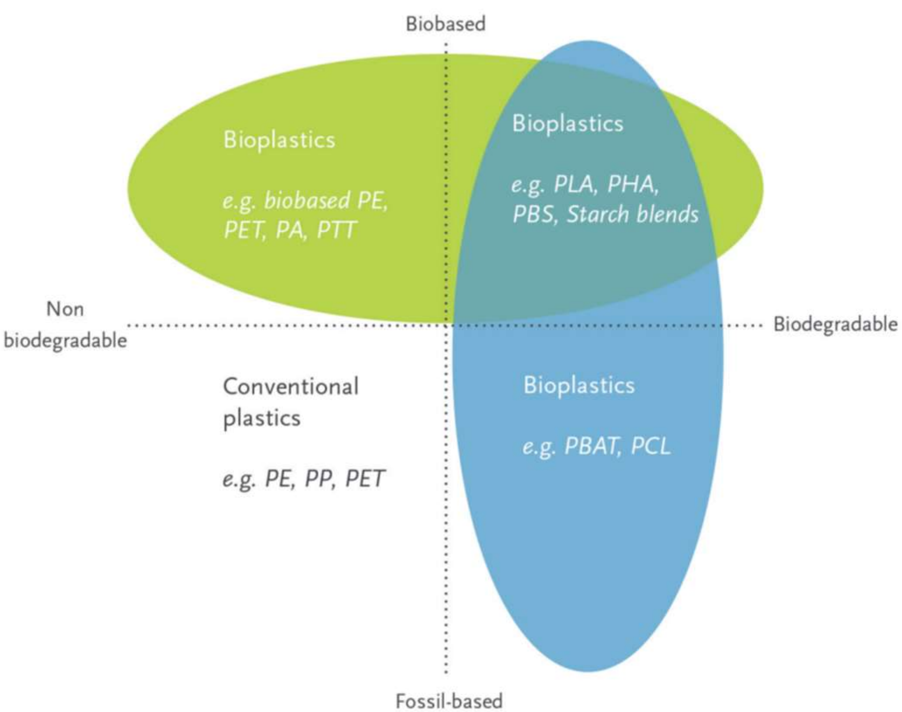
DIRECTIVE (EU) 2018/851 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL
of 30 May 2018
amending Directive 2008/98/EC on waste
(Text with EEA relevance)

DIRECTIVE (EU) 2018/852 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL
of 30 May 2018
amending Directive 94/62/EC on packaging and packaging waste
(Text with EEA relevance)

BIOPLASTICS

We need more BIOPLASTICS

- **Bioplastic types**



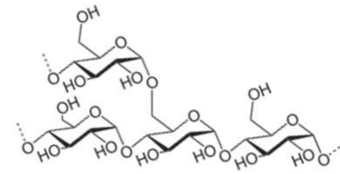
Conventional polymers	Fossil-based Non biodegradable	**PE**	Polyethylene
		PP	Polypropylene
		PET	Poly(ethylene terephthalate)
Biopolymers	Fossil-based Biodegradable	**PBAT**	Poly(butylene adipate-co-terephthalate)
		PCL	Polycaprolactone
Biopolymers	Bio-based Non biodegradable	**PE**	Polyethylene
		PET	Poly(ethylene terephthalate)
		PA	Polyamides
		PTT	Polytrimethyleneterephthalate
Biopolymers	Bio-based Biodegradable	**PLA**	Polylactic acid
		PHA	Polyhydroxalcanoate
		PBS	Polybutylene succinate
		Starch blends	

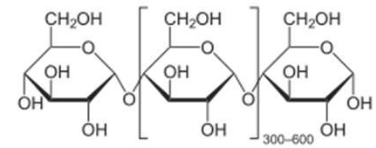
European Bioplastics: https://docs.european-bioplastics.org/publications/fs/EuBP_FS_What_are_bioplastics.pdf

BIOPLASTICS PRODUCTION (BIOBASED & BIODEGRADABLE)

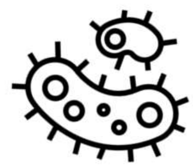
- **Production of bioplastics:**

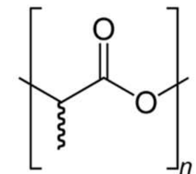
  - **Starch** → mainly produced from **agricultural** resources such as maize (70%), potatoes (12%), wheat (8%), tapioca (9%)



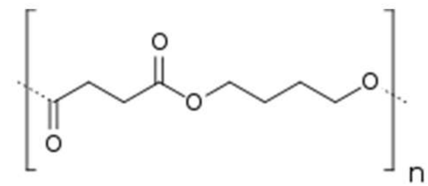


  - **PLA** → Polymerization of **lactic acid** from bacterial fermentation (*Streptococus, Lactobacillus (L.) delbrueckii, L. amylophilus, L. bulgaris* or *L. leichmanni)* of plant Starch (corn, cassava, sugarcane or sugar beet pulp)

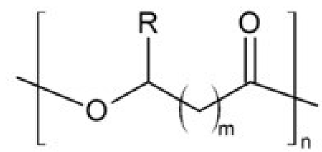




  - **PBS** → Polymerization of **succinic acid** from (*Actinobacillus succinogenes*, *Anaerobiospirillum succiniciproducens*, *Corynebacterium glutamicum*, *Escherichia coli*, *Mannheimia succiniciproducens*, *Basfia succiniciproducens*, and *Saccharomyces cerevisiae)*



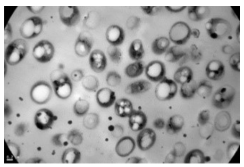
  - **PHA** → Naturally produced by bacteria:
    - Production of PHA by heterotrophic fermentation
    - Production of PHA by autotrophic photosynthesis

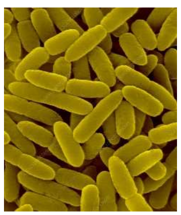


PHA FROM BACTERIA AND CYANOBACTERIA

- **PHA bacterial strains**

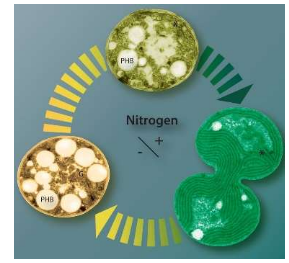

Aeromonas hydrophila


Cupravidus necator

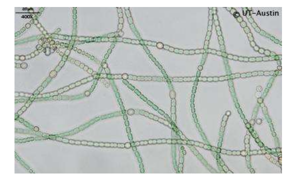

Pseudomonas citronellolis

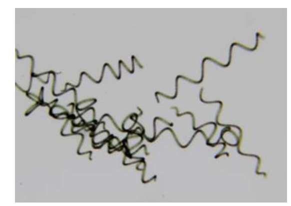

Burkholderia cepacia

Bacteria	Cyanobacteria
Aeromonas hydrophila	*Synechocystis sp.*
Azohydromonas lata	*Synechocystis salina*
Burkholderia cepacia	*Synechococcus sp. MA19*
Burkholderia sacchari	*Synechococcus subsalsus*
Cupriavidus necator	*Synechococcus elongates*
Delftia acidovornas	*Spirulina subsalsa*
Pseudomonas citronellolis	*Spirulina sp. LEB18*
Pseudomonas entomophila	*Spirulina platensis*
Pseudomonas pseudoflava	*Nostoc muscorum*
Pseudomonas putida	*Aulosira fertilissima*
Rhodospirillum rubrum	*Synechococcus sp.*
…	…



Synechocystis sp.

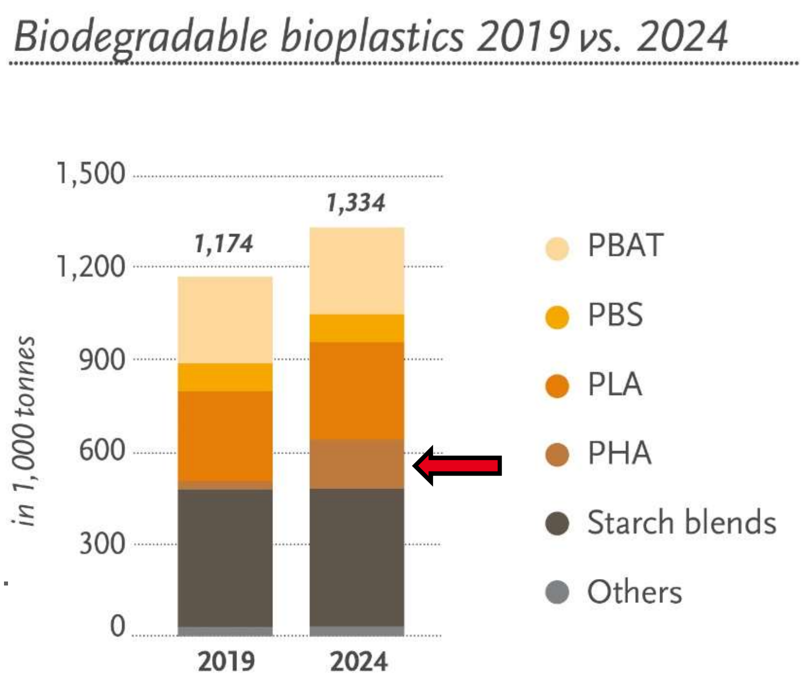

Nostoc muscorum


Spirulina platensis

Koller et al. (2017) Producing microbial polyhydroxyalkanoate (PHA) biopolyesters in a sustainable manner
Serra Costa et al. (2019) Microalgae as source of polyhydroxyalkanoates (PHAs) — A review
Cesario et al. (2014) Enhanced bioproduction of poly-3-hydroxybutyrate from wheat straw lignocellulosic hydrolysates
Rueda et al. (2020) Polyhydroxybutyrate and glycogen production in photobioreactors inoculated with wastewater borne cyanobacteria monocultures

BIOPLASTICS MARKET

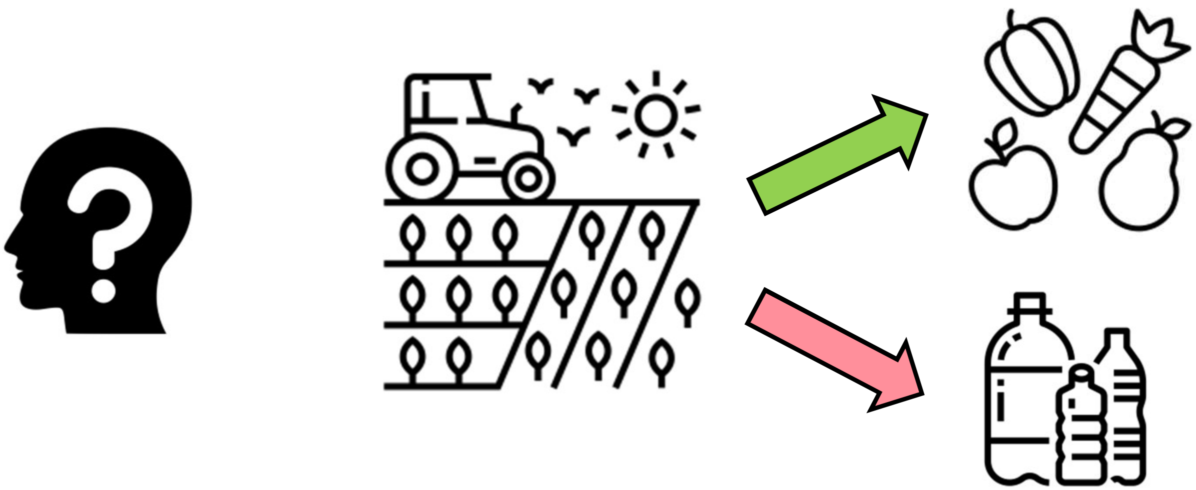
- **Bioplastics market size** (biodegradable/non biodegradable) in volume **2,11 million tons (2019)**
  - Starch blends → 21.3%
  - PLA → 13,9%
  - PBS → 4,3%
  - PHA → 1,2%
- **All are predicted to grow…**
- **PHA Prices:**
  - **PHA** biopolymer production is **3,8-4,6 €/kg**
    1-1,3 €/kg for conventional PE and PP (**3-4** times higher). (Kourmentza *et al.*, 2017)
  - The **price** of the **substrate 45%** of the overall production cost. (Kourmentza *et al.*, 2017)
  - **Recovery** process **50%** (Chen et al., 2001)
    20% the **solvent** (Aramvash *et al.*, 2018).



Source: European Bioplastics, nova-Institute (2019)
More information: **www.european-bioplastics.org/market** and **www.bio-based.eu/markets**

BIOPLASTICS PROBLEMS

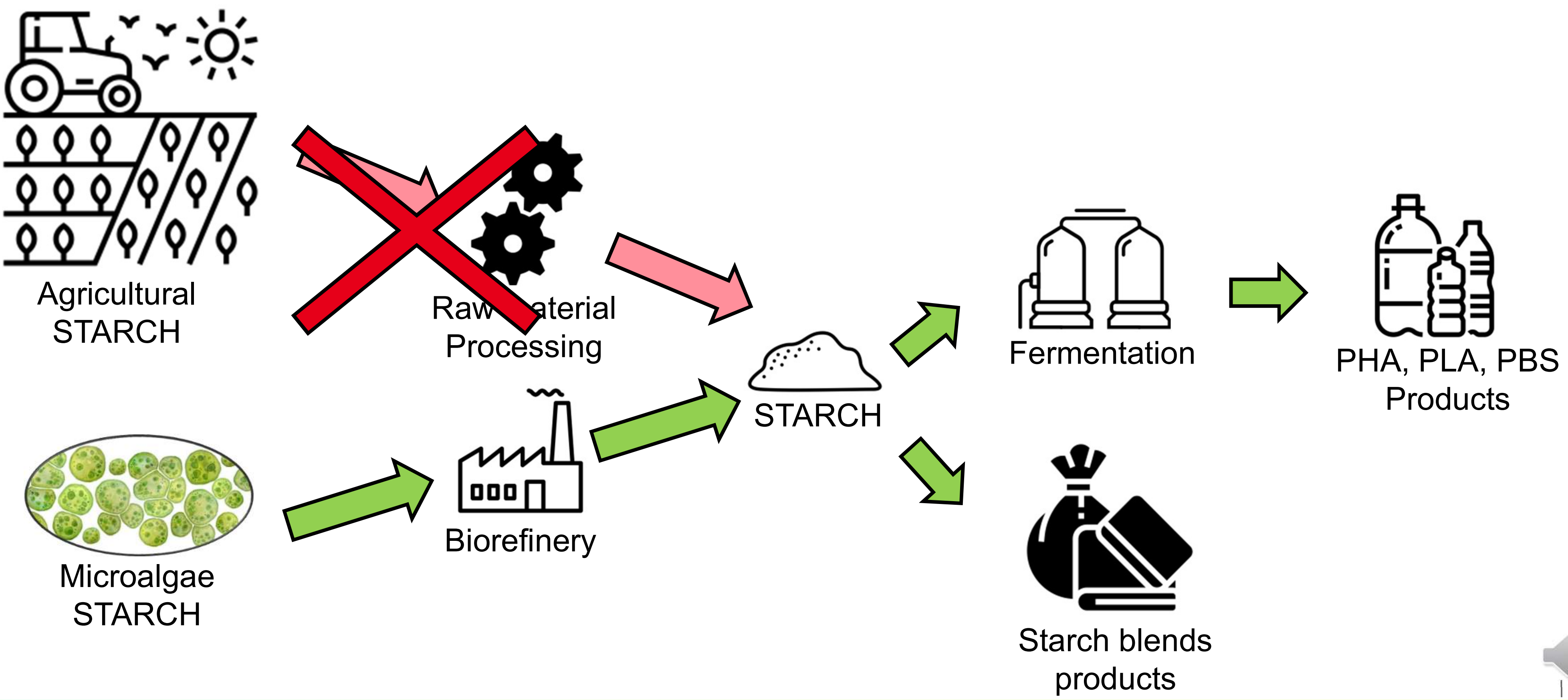
- Nowadays, **bioplastics** are derived from **terrestrial crops** such as corn and potatoes and thus **compete** with **food** supplies…



Need to stablish new value chains for **BIOPLASTICS**

KEY CONCEPT: STARCH FROM MICROALGAE

PHA from agricultural starch → PHA from agricultural starch



KEY CONCEPT: STARCH FROM MICROALGAE

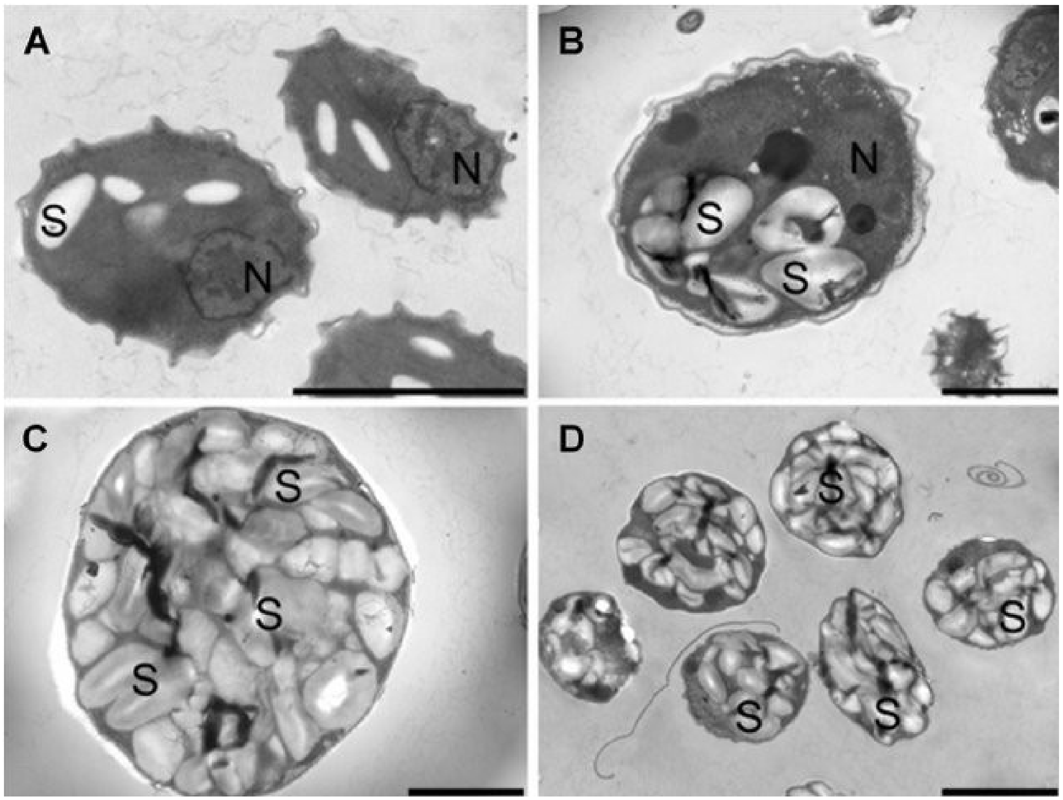
Starch production in microalgae under different nutrient status.

Strain	Nutrient stress	Starch concentration (g L^{-1})	Starch productivity (g L^{-1} d^{-1})	Starch content (%DW)	Refs.
Spirulina sp. LEB 18[a]	± N (3 mM)	0.57	0.04	59.1	da Silva Braga et al. (2018)
Arthrospira platensis[a]	± N (3 mM)	1.03	0.29	65	Aikawa et al. (2012)
Synechococcus sp. PCC 7002[a]	± N (15 mM)	3.5	0.50	49.8	Aikawa et al. (2014)
A. platensis[a]	± P (57.4 µM)	0.52	0.052	59.9	Markou et al. (2012)
Chlorella sorokiniana str. SLA-04	-N	-[b]	0.012	20	Hanifzadeh et al. (2018)
Chlorella sorokiniana	-N	–	0.17	38	Gifuni et al. (2018)
Chlamydomonas reinhardtii	-N	0.79	0.18	69.3	Gardner et al. (2013)
Chlorella sp. AE10	± N (4.4 mM)	1.42	0.69	56.9	Yuan et al. (2018)
	± P (26.3 µM)	0.19	–	42.8	
	± S (36.5 µM)	0.69	–	53.1	
Chlorella sp. AE10	± N (4.4 mM)	1.21	0.73	60.5	Cheng et al. (2017)
Tetraselmis subcordiformis	–N	0.70	0.49	54.0	Yao et al. (2012)
	± N (3 mM)	1.8	0.42	51.1	
	± N (11 mM)	2.7	0.30	47.8	
	–S	1.2	0.62	62.1	
Tetraselmis subcordiformis	–P	1.1	0.29	44.1	Yao et al. (2013)
Tetraselmis subcordiformis	-N + P (3 mM)	1.0	0.5	64.5	Yao et al. (2018)
Scenedesmus obliquus CNW-N	± N (1 mM)	2.25	0.17	50.0	Ho et al. (2017a)
	± N (4 mM)	1.88[c]	0.27[c]	49.4[c]	Ho et al. (2013)
Chlorella vulgaris Beijerinck CCALA924	–N	0.10	0.19	37	Brányiková et al. (2011)
	–P	0.35	0.48	53	
	–S	0.62	0.74	60	
C. vulgaris Beijerinck, P12	–N	–	0.199	41.0	Dragone et al. (2011)
Parachlorella kessleri	–S	0.25	0.036	50.5	Mizuno et al. (2013)

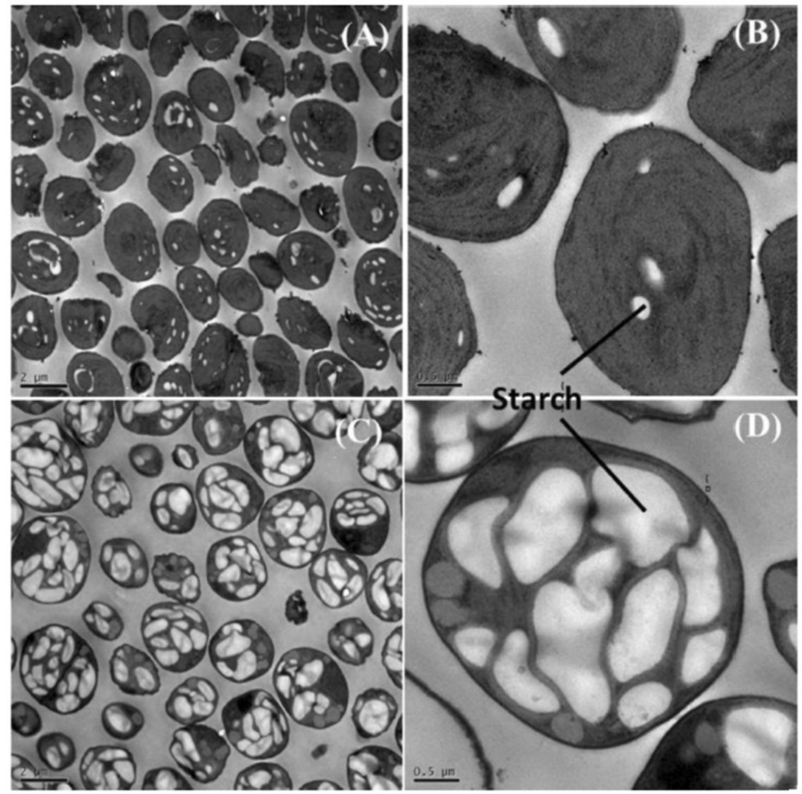
Ran et al. (2019) Storage of starch and lipids in microalgae: Biosynthesis and manipulation by nutrients

KEY CONCEPT: STARCH FROM MICROALGAE

- **Starch granules in stressed *Chlorella vulgaris* (60% starch)**



Branyikova et al., (2011) Microalgae - Novel Highly Efficient Starch Producers



Cheng et al., (2017) Improving carbohydrate and starch accumulation in Chlorella sp. AE10 by a novel two-stage process with cell dilution.

2 EU MICROALGAE PROJECTS AT CEA

- **NENU2PHAR**
- **Topic: BBI-2019-SO3-R8 (BIOBASED INDUSTRIES)**
- **Type of action: BBI-RIA**
- Objective: microalgae starch → PHA

Horizon 2020
European Union Funding
for Research & Innovation

NENU2PHAR

BBI JU

Bio-based Industries Consortium

N° 887474

https://cordis.europa.eu/project/id/887474

- **SEALIVE**
- **Topic: CE-BG-06-2019 (BLUE GROWTH)**
- **Type of action: IA**
- Objective: starch, PHA and PLA

SEALIVE

Strategies of circular Economy and Advanced bio-based solutions to keep our Lands and seas alIVE from plastics contamination

N° 862910

https://sealive.eu/

2 EU microalgae projects at CEA

Grant agreement ID: 887474

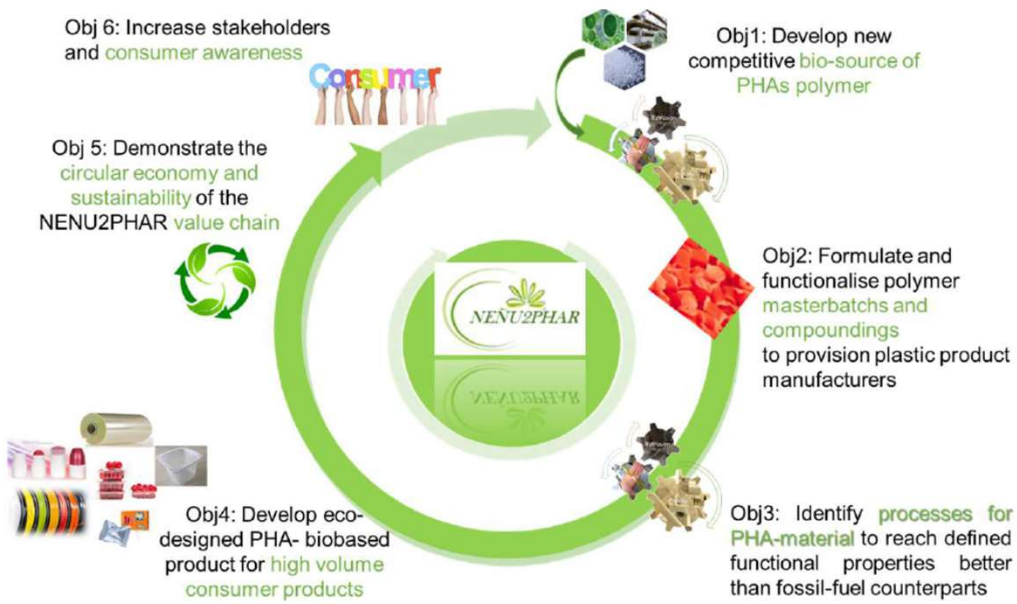
NENU2PHAR CONCEPT

The goal of **NENU2PHAR** is to set up a new **European value chain** of **PHA-based bio-plastic products** from a **sustainable bio-source** with an **acceptable End of Life**.

NENU2PHAR concept targets the **development** of high-performance **bioplastic materials** and **products** with **better environmental profile** which are key for the **sustainable growth** of the **plastic industry**.

NENU2PHAR proposes an inclusive approach that will **address the whole PHA-based plastic value chain, from bio-source to finished products**.

NENU2PHAR Circular economy value chain approach



2 EU microalgae projects at CEA

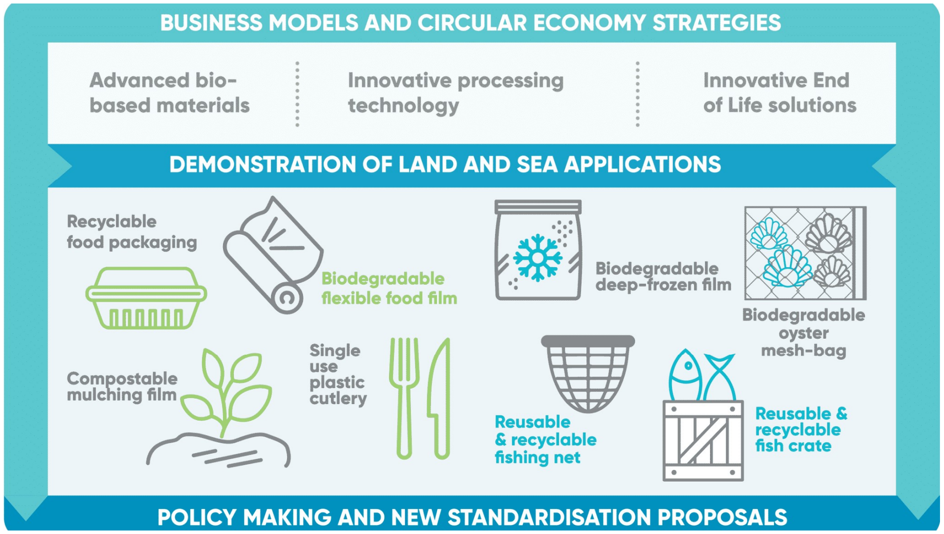
SEALIVE CONCEPT

SEALIVE will bring advanced bio-based plastic solutions to the **market**, providing viable **alternatives** to single-use plastics.

SEALIVE will **reduce plastic waste** and contamination on **land** and in **seas** by boosting the use of biomaterials and contributing to the circular economy with cohesive bio-plastic strategies.

- New bio-based plastics solutions (**PLA, PHA, starch** and **novel blends**) with advanced properties.
- **Recycling-by-design** techniques.
- Effective **end of life solutions** targeting circular economy (NIR sorting, polymer markers, compostability, marine degradation).

SEALIVE Circular economy value chain approach



2 EU microalgae projects at CEA

NENU2PHAR AT A GLANCE

- Kick-Off → September 2020
- Budget→ 6,4M€
- 727 Man Months
- 8 EU Countries:
  FR, ES, NL, BE, PL, HR, PT, MC
- 16 partners:
  - 4 RTO
  - 1 Academic
  - 1 Association
  - 6 SME
  - 4 Large Industries

RTO
cea tech, CENTEXBEL, Innovation Plasturgie Composites, ITENE

ACADEMY
IRDL – Institut de Recherche Dupuy de Lôme UMR CNRS 6027

ASSOCIATION
IAR – Le Pôle de la Bioéconomie

SME
Elixance, celabor, biotrend, Lomartov, Zero-E Engineering, bio-mi

INDUSTRY
Sofradim Production, IFG International Fibres Group, KAJ packaging solutions, Danone

2 EU microalgae projects at CEA

SEALIVE AT A GLANCE

- Kick-Off → October 2019
- Budget → 10.26M€
- 1198 Man Months
- 13 Countries:
  AT, BE, CY, CZ, DK, FR, GE, IRL, IT, NL, PT, ES and AR
- 24 partners:
  - 4 RTO
  - 2 Academic
  - 4 Non Profit Org
  - 10 SME
  - 4 Large Industries

RTO

ACADEMY

OTHER

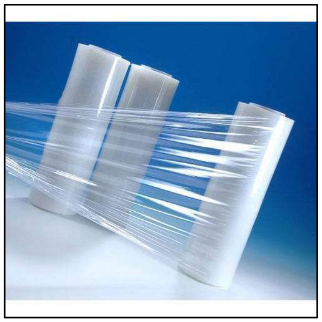
SME

INDUSTRY

2 EU microalgae projects at CEA

Grant agreement ID: 887474

Flexible transparent packaging film

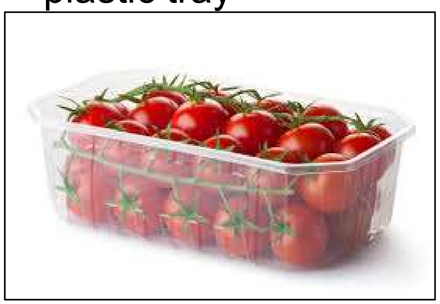


Roll on bottle for cosmetic application

3D printing filament

Woven groundcovers

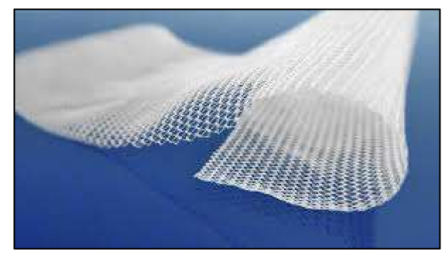
Thermoformed food plastic tray



Stand up pouch for dry food

Plastic cup container for compote

Medical devices surgical mesh



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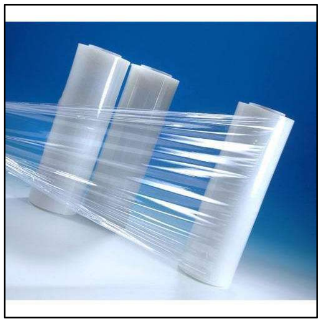
Flexible transparent packaging film



Thermoformed food plastic tray

Single used plastic products

Mulching film

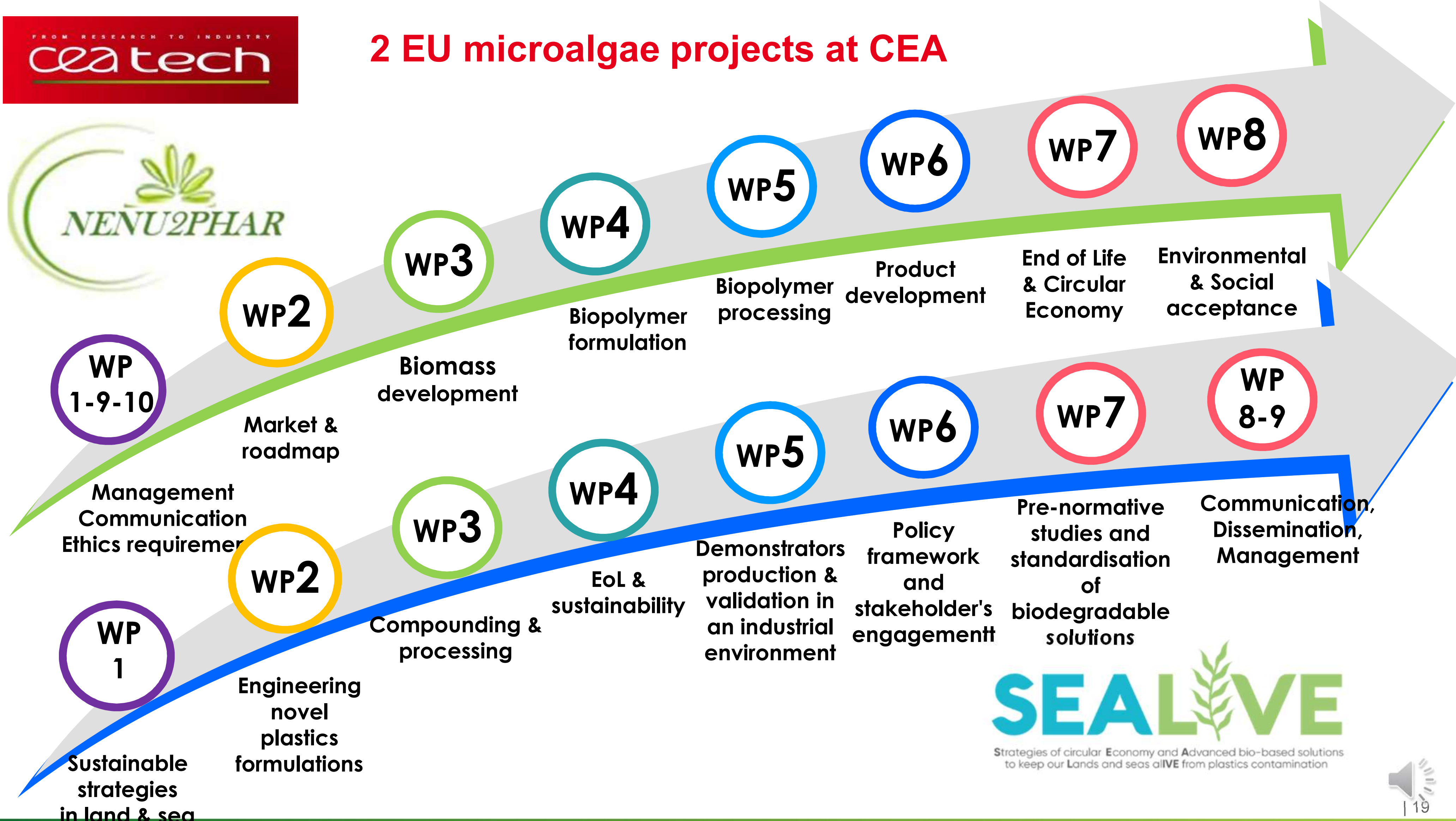
Flexible food packaging

Fish crates

Fishing nets

Oyster meshbag

2 EU microalgae projects at CEA



2 EU microalgae projects at CEA

WP3 **Biomass development**

WP2 **Engineering novel plastics formulations**

Culture of microalgae to generate **starch** biopolymer

Upscaling production **of algae** biomass

Hydrolysis of **starch-enriched biomass**

Fractionation of biomass and **extraction** into biopolymer

Fermentation of bacteria to generate **PHA**

Up scaling full **PHA production** chain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SEALIVE

DE LA RECHERCHE À L'INDUSTRIE

BIOREFINERY OF *CHLORELLA VULGARIS*: NEW PATHWAYS DEVELOPED FOR BIOPLASTICS

Compadre A., Dubreuil C., Mandon P., Vogt G., Delrue F., Alvarez P., Fleury G., Mailley S., Sassi J.F.

AlgaEurope 2020 (01-04/12/2020)

Commissariat à l'énergie atomique et aux énergies alternatives - www.cea.fr

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