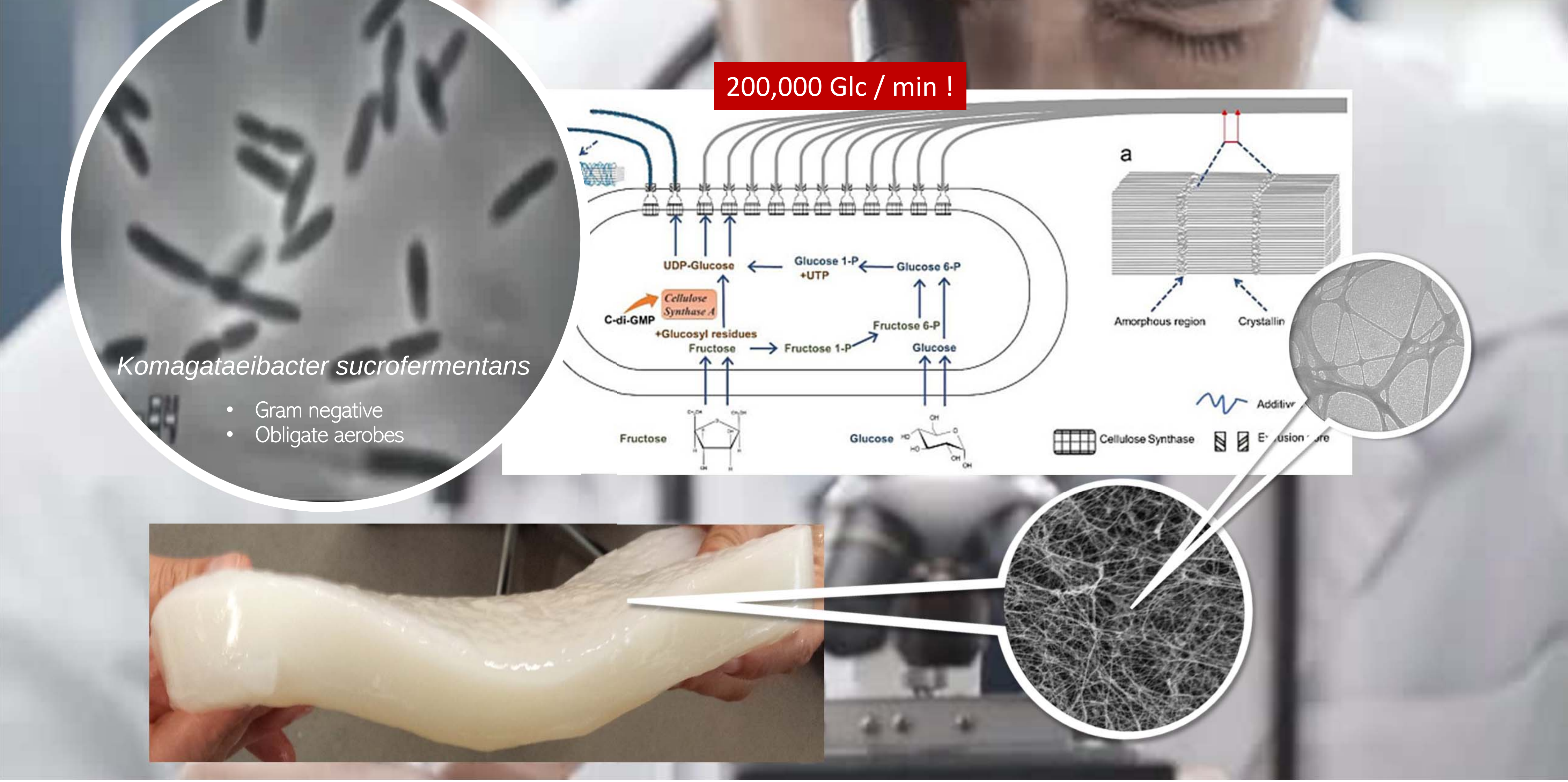
Economic & environmental assessment of bacterial cellulose production

Ana Forte, Fernando Dourado, Miguel Gama, Eugénio C. Ferreira

Centre of Biological Engineering,
University of Minho, Campus de Gualtar, 4710-057 Braga, Portugal

What is Bacterial Cellulose?



Appealing properties

Properties		References
Degree of polymerization	up to 8000	(Wu et al., 2016)
Crystallinity	60–90%.	(Klemm et al., 2005)
Nanofibers' diameter	20–100 nm	(Wu et al., 2016)
Nanofibers' length	1–9 µm	(Foresti, Vázquez and Boury, 2017)
Density	$1.50\ g{\cdot}cm^{-3}$ $1.25\ g{\cdot}cm^{-3}$	(Hervy et al., 2018) (Lee, Blaker and Bismarck, 2009b)
Surface area	$2.7–37\ m^{2}{\cdot}g^{-1}$	(Kim, Nishiyama and Kuga, 2002)
Water absorption	610.5 - 320%	(Potivara and Phisalaphong, 2019) (Rathinamoorthy et al., 2019)
Water vapor permeability	$765.95–1045.55\ g{\cdot}m^{-2}{\cdot}day^{-1}$ $2.38{\times}10^{-11}\ g{\cdot}m^{-1}{\cdot}s^{-1}{\cdot}Pa^{-1}$ $151\ g{\cdot}m^{-2}{\cdot}day^{-1}$ $1.26{\times}10^{-10}\ g{\cdot}m^{-1}\ h^{-1}{\cdot}Pa^{-1}$ $1–11{\times}10^{-13}\ g{\cdot}m^{-1}{\cdot}s^{-1}{\cdot}Pa^{-1}$	(Kamal, Misnon and Fadil, 2020) (Cazón, Velázquez and Vázquez, 2019) (Rathinamoorthy et al., 2019) (Jebel and Almasi, 2016) (Tomé et al., 2010)
Young's modulus	1044 MPa 5–17 GPa 93.8 MPa 138 GPa 114 GPa 15–35 GPa	(Cazón, Velázquez and Vázquez, 2019) (Potivara and Phisalaphong, 2019) (Jebel and Almasi, 2016) (Hu et al., 2011) (Lee, Blaker and Bismarck, 2009b) (Klemm et al., 2005)
Tensile strength	20.8 MPa 70–300 MPa 26.3 MPa 2 GPa 200–300 MPa	(Cazón, Velázquez and Vázquez, 2019) (Potivara and Phisalaphong, 2019) (Jebel and Almasi, 2016) (Hu et al., 2011) (Klemm et al., 2005)
Elongation	2.3% 0.5%–5.0% 6.1 % 1.5–2.0%	(Cazón, Velázquez and Vázquez, 2019) (Potivara and Phisalaphong, 2019) (Jebel and Almasi, 2016) (Klemm et al., 2005)

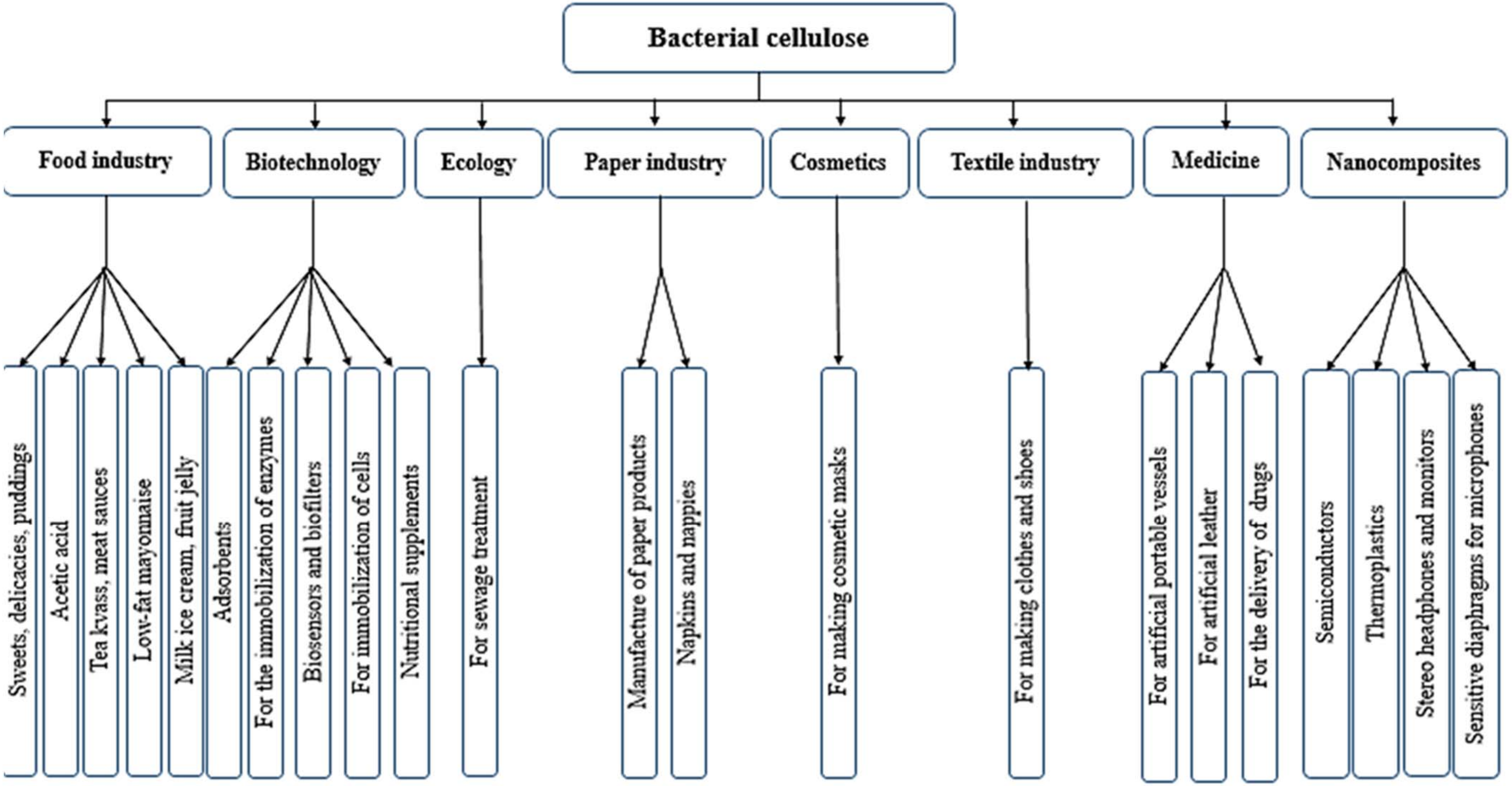
 Appl Microbiol Biotechnol (2018) 102:6885–6898

Table 1 Bacterial cellulose productivity (g/L/days) by AAB in different conditions

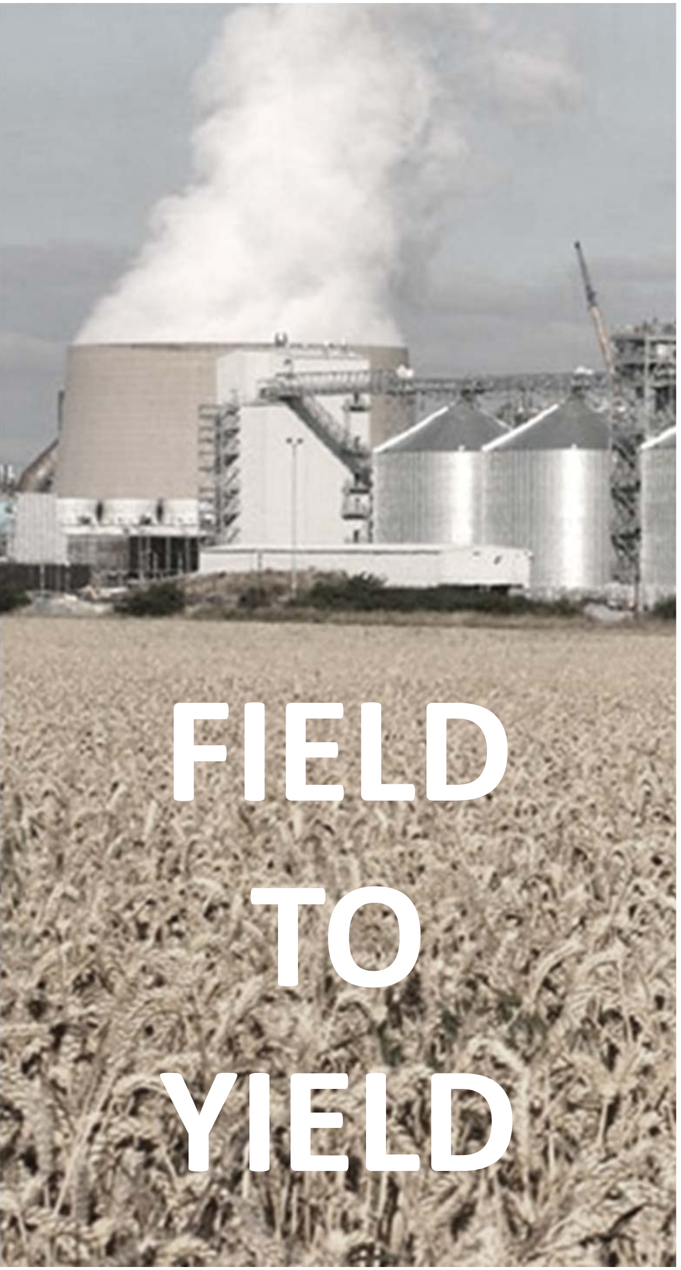
Present name[a]	Carbon source/feedstock		System	Time (days)	Productivity (g/L/days)	Reference
	Type	Amount (g/L)				
K. xylinus AX2-16	Glucose	25	Static	8	1.47	Zhong et al. (2013)
K. hansenii PJK=KCTC10505BP	Glucose Acetic acid Succinate Ethanol	10 1.5 mL 2 10	Submerged	2	0.86	Jung et al. (2005)
K. xylinus BRC5=KCCM 10100	CSL: Glucose Citric acid	80 20 1.15	Submerged	2	7.65	Hwang et al. (1999)
K. rhaeticus P1463	Apple juice Glucose Fructose Sucrose	 3 12.4 4.6	Static	14	0.68	Semjonovs et al. (2017)
K. hansenii B22	Apple juice: Glucose Fructose Sucrose	 3 12.4 4.6	Static	14	0.50	Semjonovs et al. (2017)
K. xylinus K2G30=UMCC 2756	Glucose Ethanol	50 14	Static	15	1.31	Gullo et al. (2017)
K. xylinus ATCC 23767[T]	CSL: Glucose Xylose Mannose Acetic acid	 3.87 29.61 1.84 18.73	Static	7	0.41	Cheng et al. (2017)
K. xylinus BCRC 12334	Glucose	60	Static	14	0.52	Kuo et al. (2015)
K. xylinus ATCC 23770	HFS: Glucose	 14.1	Static	7	1.57	Cavka et al. (2013)
K. hansenii M2010332	Glucose Citric acid Ethanol	55 1 20	Static	7	2.33	Li et al. (2012)
Gluconacetobacter sp. st-60-12 and *Lactobacillus* sp. st-20	CSL: Sucrose	40 40	Submerged	3	1.4	Seto et al. (2006)
K. xylinus BPR2001	CSL: Fructose Inositol	 40 0.002	Submerged	2.5	3.2	Noro et al. (2004)
K. xylinus BPR2001	CSL: Sucrose	 37	Static	3	1.8	Bae and Shoda (2005)

CSL corn steep liquor, *HFS* hydrolysate fiber sludges

[a] The present names of AAB species are reported, according to LPSN bacterio.net (Euzéby 1997)



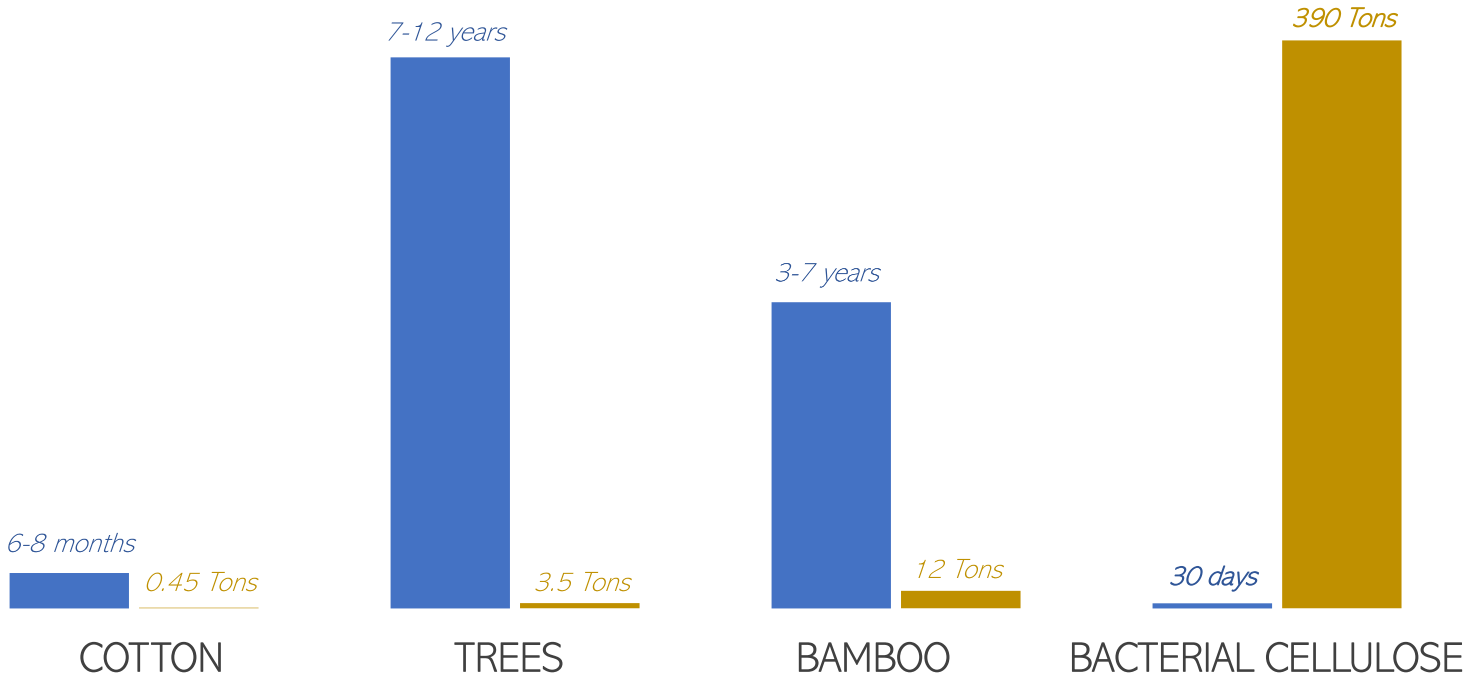
Niyazbekova *et al*. (2018). An Overview of Bacterial Cellulose Applications. Biotechnology. Theory and practice. 10.11134/btp.2.2018.3.



Advantages of bacterial cellulose fermentation technology

Reference area: football field

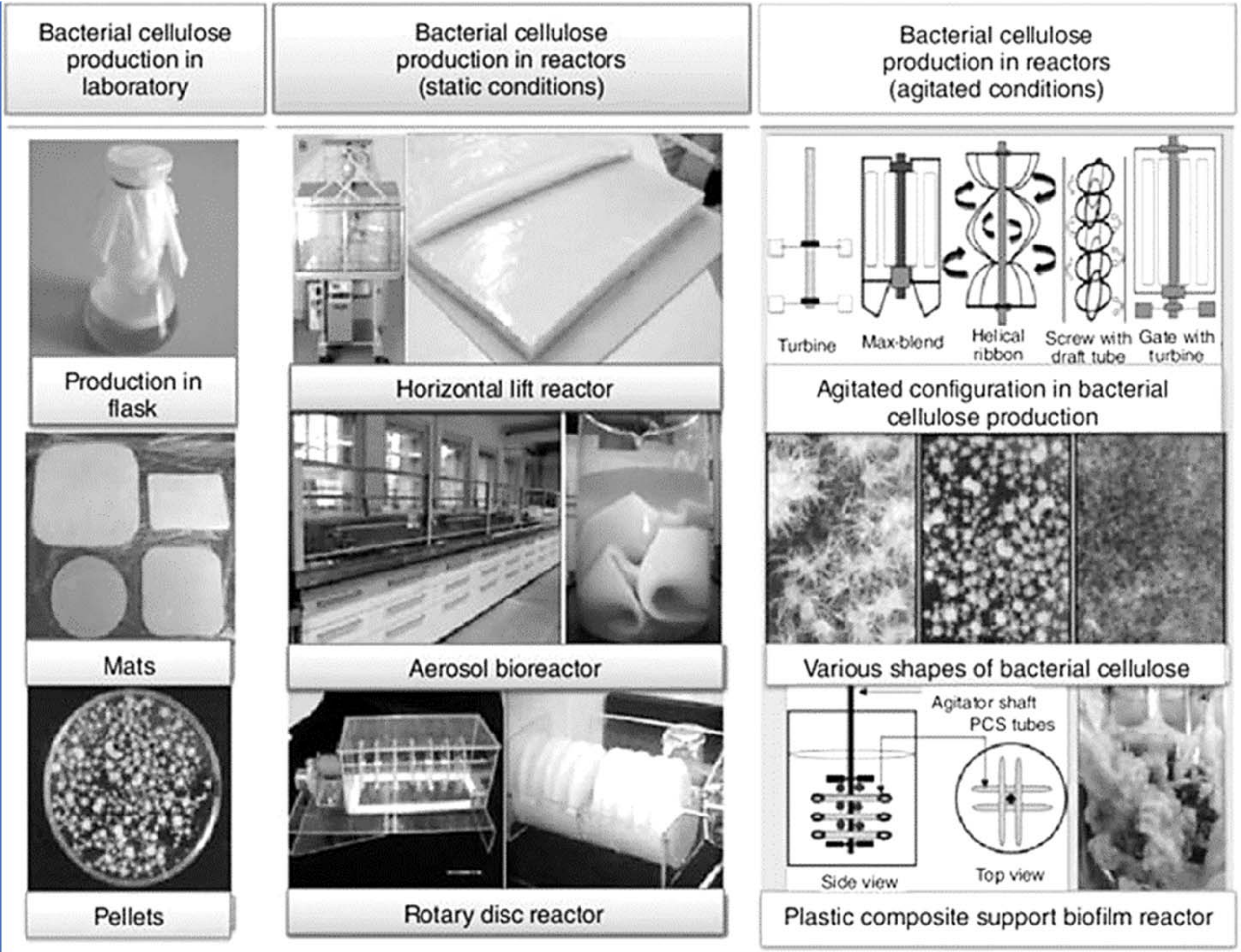
The combination of **recyclability, sustainability, biodegradability** and new end-use opportunities makes BC the potential super material of the future.



Efforts towards cost-effective BC production

Different strains
Different media composition
Different culture conditions

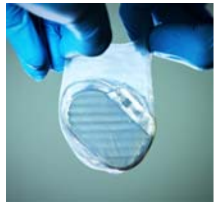
Low BNC yields



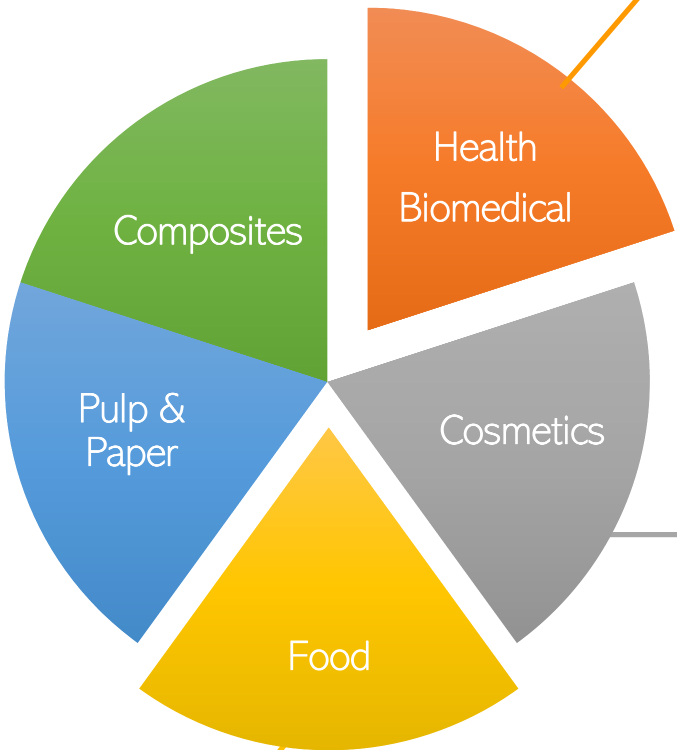
Dourado, F., et al. (2016). Bacterial Nanocellulose. Amsterdam, Elsevier: 199-214

Ullah, M.W., Manan, S., Kiprono, S.J., Ul-Islam, M. and Yang, G. (2019). Nanocellulose (eds J. Huang, A. Dufresne and N. Lin).

Appealing marketable applications
(but confined mostly to health/biomedical)



● Active companies



High value-added Nich markets

Xylos (USA)
Biofill (Brazil)
JenNaCell (Germany)
Hylomorph (Switzerland)

Gengiflex®
(surgery and dental implants)

Bioprocess®
XCell®
Biofill®
Dermafill®
Gengiflex®
(wound dressings)

Low value-added Large volume

Nata de coco:
Asian Countries
(several companies)

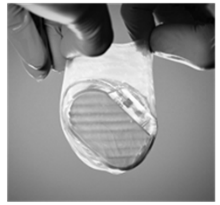
Cellulon®, Primacel®:
Cetus Co. (USA)
Weyerhaeuser Co. (USA)

Asian Countries
(several companies)

Bowil Biotech (Poland)

CPKelco (USA) AxCel®PX, AxCel®CG-PX, AxCel®PG, Cellulon™PX….

Appealing marketable applications
(but confined mostly to health/biomedical)



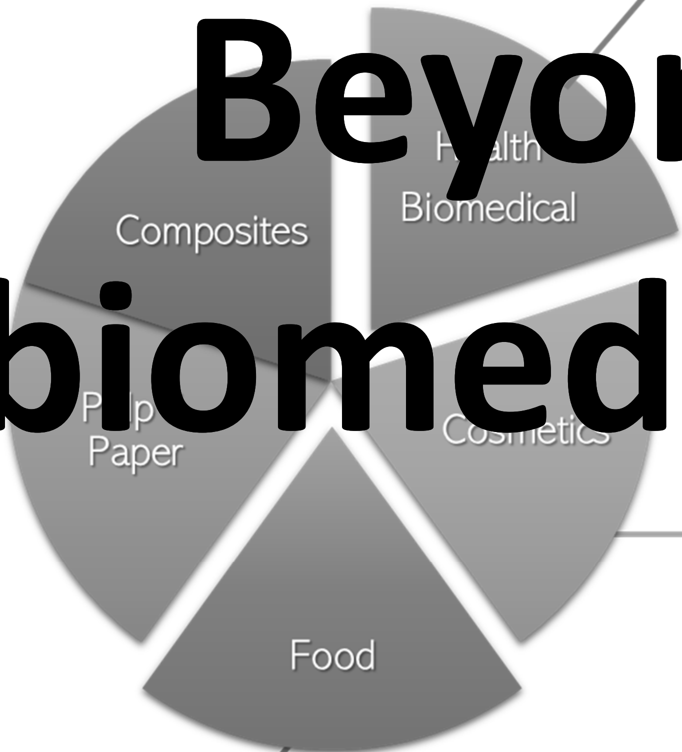
Beyond biomedical?

● Active companies

Low value-added
Large volume

Nata de coco:
Asian Countries
(several companies)

Cellulon®, Primacel®:
Cetus Co. (USA)
Weyerhaeuser Co. (USA)
CPKelco (USA)



High value-added
Niche markets

Xylos (USA)
Biofill (Brazil)
JenNaCell (Germany)
Hylomorph (Switzerland)

Gengiflex®
(surgery and dental implants)

Bioprocess®
XCell®
Biofill®
Dermafill®
Gengiflex®
(wound dressings)

Asian Countries
(several companies)

Bowil Biotech (Poland)

Scaling up

How expensive?

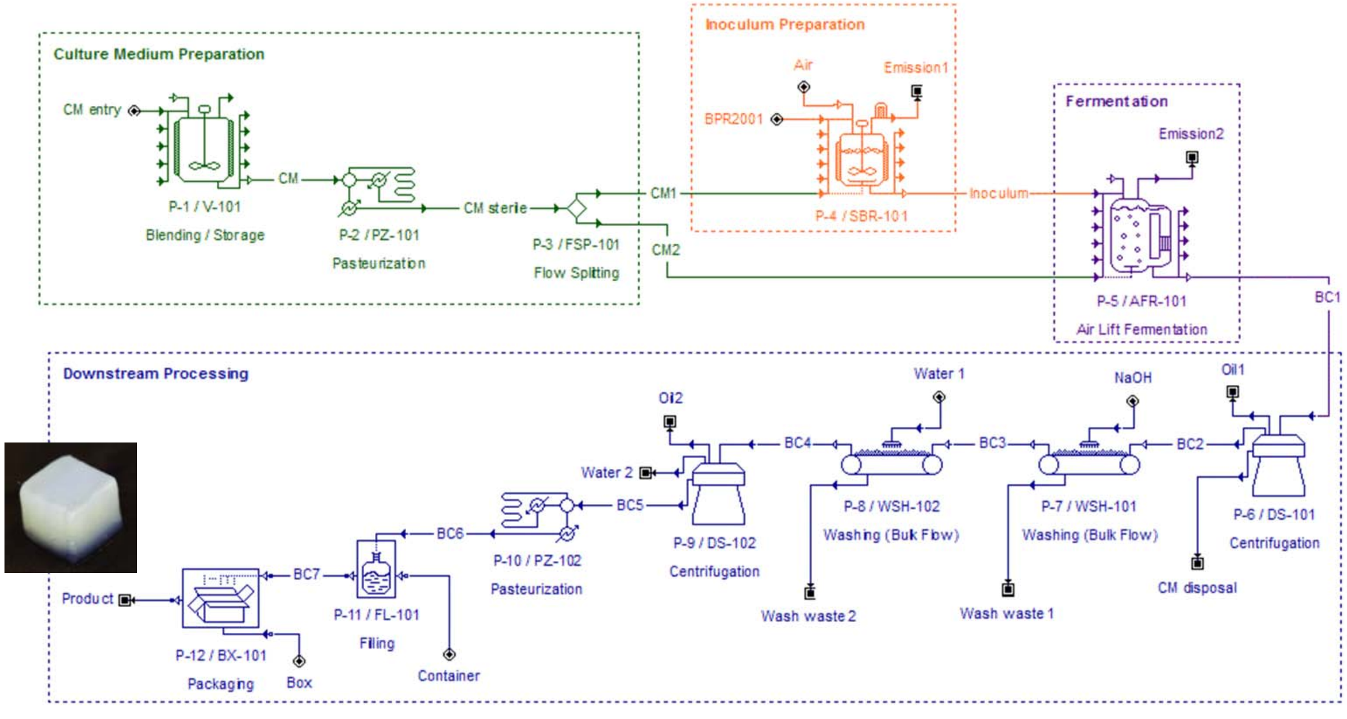
Economic assessment of the BC production

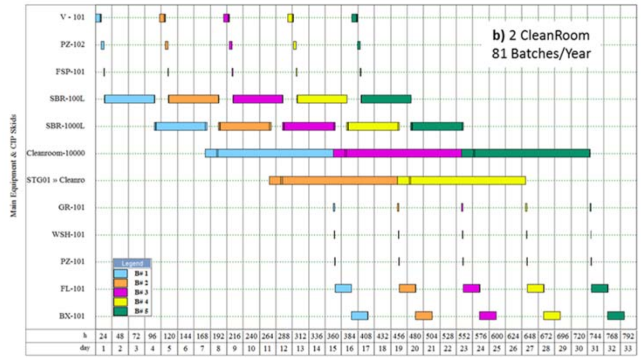
SuperPro Designer (EMA Engineering)

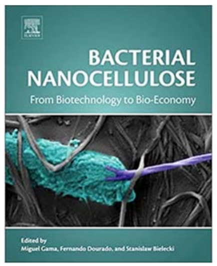
Static & agitated culture conditions

Super-Pro process flowsheet for BNC production

≈ 3.5 Ton/year, dried basis (500 Ton/year wet)



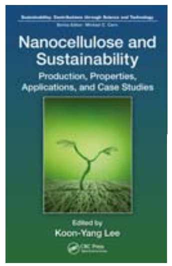




CHAPTER 12

Process Modeling and Techno-Economic Evaluation of an Industrial Bacterial NanoCellulose Fermentation Process

Fernando Dourado, Ana Fontão, Marta Leal, Ana Cristina Rodrigues, Miguel Gama
Minho University, Biological Engineering Department, Campus de Gualtar, Braga, Portugal



1 Process Modelling and Techno-Economic Evaluation of an Industrial Airlift Bacterial Cellulose Fermentation Process

Fernando Dourado, Ana Isabel Fontão, Marta Leal, Ana Cristina Rodrigues and Miguel Gama

M.S. Peters, K.D. Timmerhaus, in: M.S. Peters, K.D. Timmerhaus (Eds.) Plant Design and Economics for Chemical Engineers, McGraw-Hill, Singapore, 1991, pp. 150-215.

Capital Investment Cost (M USD$)	AGITATED	STATIC
Direct Costs (DC)	12.5	9.2
Indirect Costs (IC)	3.1	2.1
Fixed Capital Investment (FCI)	*15.6*	*11.3*
Working Capital (WC)	*2.3*	*1.7*
TOTAL CAPITAL INVESTMENT (TCI)	17.9	13.0

Estimation of the Annual Product Manufacturing Cost (M USD$)		
Manufacturing Costs (MC)	***6.25***	***5.4***
Direct Production Cost (Variable costs)	2.4	2.2
Fixed charges	3.0	2.1
Plant overhead Costs (50-70% OL, DS & CL, and M & R)	0.85	1.1
General Expenses (GE)	***1.8***	***2.0***
TOTAL PRODUCT COST (TPC): MC + GE	8.0	7.4

Profitability (M USD$) (500 MTon/year, at a selling price of 25 USD$/Kg)		
Total income: Selling Price X Quantity of product	12.5	12.5
Gross income: Total Income - Total Product Cost	4.5	5.1
Taxes: 30-40% Gross Income	1.6	1.8
Net Profit: Gross Income - Taxes	3.0	3.4
Rate of Return: Net Profit*100/TCI	7%	11%
Payout Period: FCI/(Net Profit + Depreciation)	5 Years	4 Years

≈ 3.5 Ton/year:

≈ 3600 USD$/Kg dried BC!

(Asian Countries ≈ 60 USD$/Kg dried nata de coco)

Dourado, F., et al. (2016). Process Modeling and Techno-Economic Evaluation of an Industrial Bacterial NanoCellulose Fermentation Process. Bacterial Nanocellulose. Amsterdam, Elsevier: 199-214

Dourado, F., et al. (2017). Process modelling and techno-economic evaluation of an industrial air-lift bacterial cellulose fermentation process. Nanocellulose and Sustainability: Production, Properties, Applications, and Case Studies. CRC Press *in press*.

And what about the wastewaters?

Biodegradation (2020) 31:47–56
https://doi.org/10.1007/s10532-020-09893-z

ORIGINAL PAPER

Study and valorisation of wastewaters generated in the production of bacterial nanocellulose

Francisco A. G. Soares da Silva · João V. Oliveira · Catarina Felgueiras · Fernando Dourado · Miguel Gama · M. Madalena Alves

Low cost subtrates (agroindustrial wastes)

↓

High COD, BOD!

↓

$$$ Uphill/Downhill

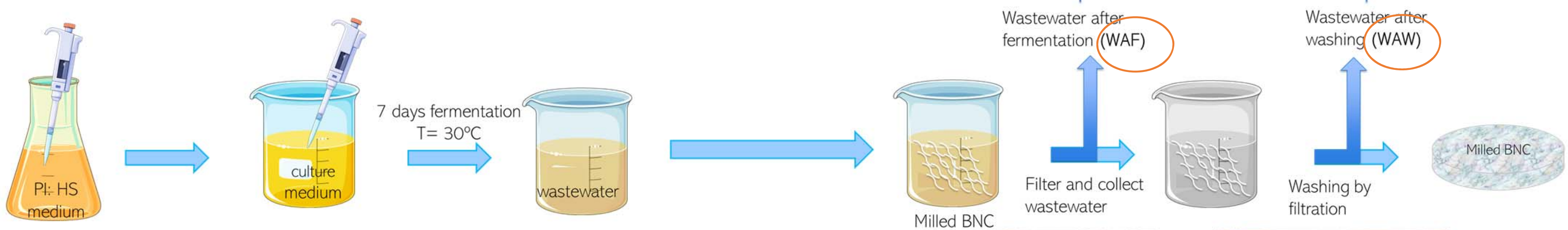
Bacterial cellulose production

Strain: *Komagataeibacter xylinum ATCC 700178*
Culture media tested:
HS-EtOH - Glucose 40.0 g·L^{-1}; peptone 5.0 g·L^{-1}; yeast extract 5.0 g·L^{-1} ;
Mol-HS - untreated molasse 40.0 g·L^{-1}; peptone 5.0 g·L^{-1}; yeast extract 5.0 g·L^{-1};
Mol-CSL - untreated molasse 40.0 g·L^{-1}; CSL 7.0 g·L^{-1}; ammonium sulphate 0.5 % (w/v));
All formulations complemented ethanol 1.5 % (v/v), disodium phosphate di-hydrated 3.39 g·L^{-1}

Wastewater characterization

- Chemical oxygen demand
- Total and volatile solids
- Total nitrogen
- Volatile fatty acids

Anaerobic digestion:
- Biochemical methane potential assays
- UASB reactor



Effluents from different culture media used for BC production

Table 1. Characterization of effluents generated in the BC production.

Parameter	Units	Culture medium		
		HS-EtOH	Mol-HS	Mol-CSL*
TS	g·L^{-1}	26.8 ± 0.4	53.1 ± 1.3	73.4 ± 1.6
VS	g·L^{-1}	21.5 ± 0.4	43.7 ± 1.0	58.1 ± 1.4
COD	g·L^{-1}	37.4 ± 5.7	54.5 ± 2.1	75.2 ± 2.5
TN	g·L^{-1}	1.51 ± 0.11	1.21 ± 0.01	1.73 ± 0.08
BNC titre	g·L^{-1}	1.79 ± 0.04	8. ± 0.29	5.95 ± 0.76

* This experiment generated the designated Wastewater after Fermentation - WaF

Table 2. Characterization of WaF and WaW as used in the batch assays.

Parameter	Units	WaF	WaW
TS	g·L^{-1}	73.4 ± 1.6	20.6 ± 0.1
VS	g·L^{-1}	58.1 ± 1.4	13.5 ± 0.1
CODt	g·L^{-1}	75.2 ± 2.5	19.2 ± 0.2
CODs	g·L^{-1}	74.3 ± 3.0	18.8 ± 0.3
TN	mg·L^{-1}	1730 ± 80	900 ± 10
VFA	g L^{-1}	nd	1.89

Biochemical methane potential of effluents from BNC fermentation of Mol-CSL

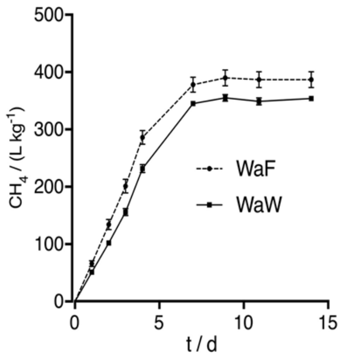
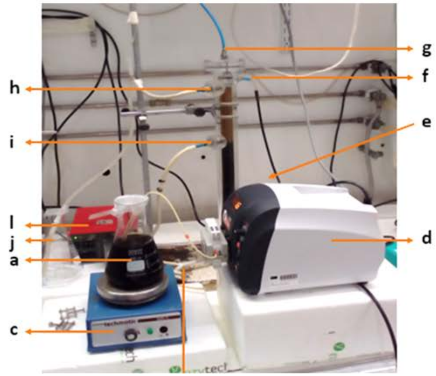


Fig1. Methane production (L·kg^{-1} of VS) present in the biogas produced with WaF and WaW per day.

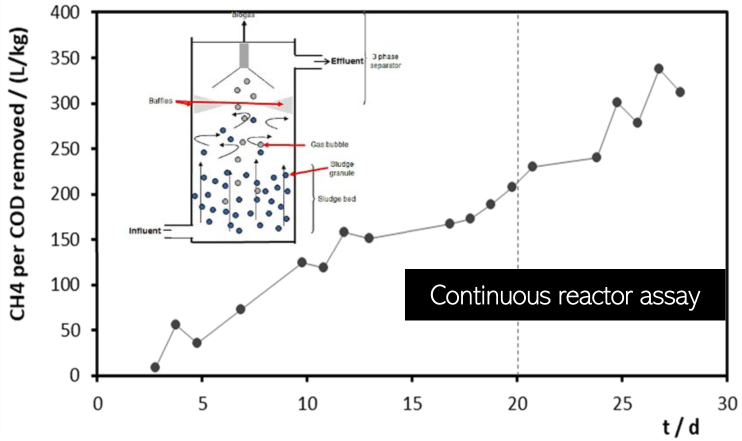
Table 3. Characterization of WaW after anaerobic biodegradability tests.

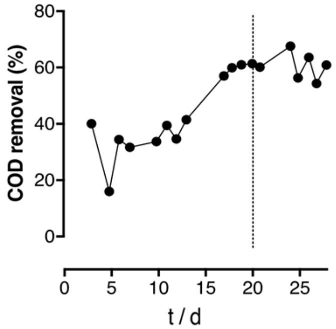
Parameter	Units	WaF	WaW
PM	%	86.9 ± 3.1	79.5 ± 0.9
CODs	g·L^{-1}	**0.72 ± 0.03**	**0.75 ± 0.10**
VFA	g·L^{-1}	n.d.	n.d.
NH_4^+	mg·L^{-1}	312 ± 35	186 ± 10
NH_3	mg·L^{-1}	9.0 ± 1.0	8.0 ± 0.0

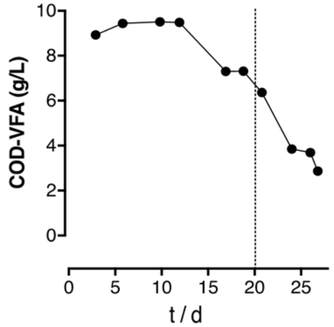
n.d. – non-detected;
Note: the BMP results presented were calculated after subtraction of blank value.



Upflow anaerobic sludge blanket reactor



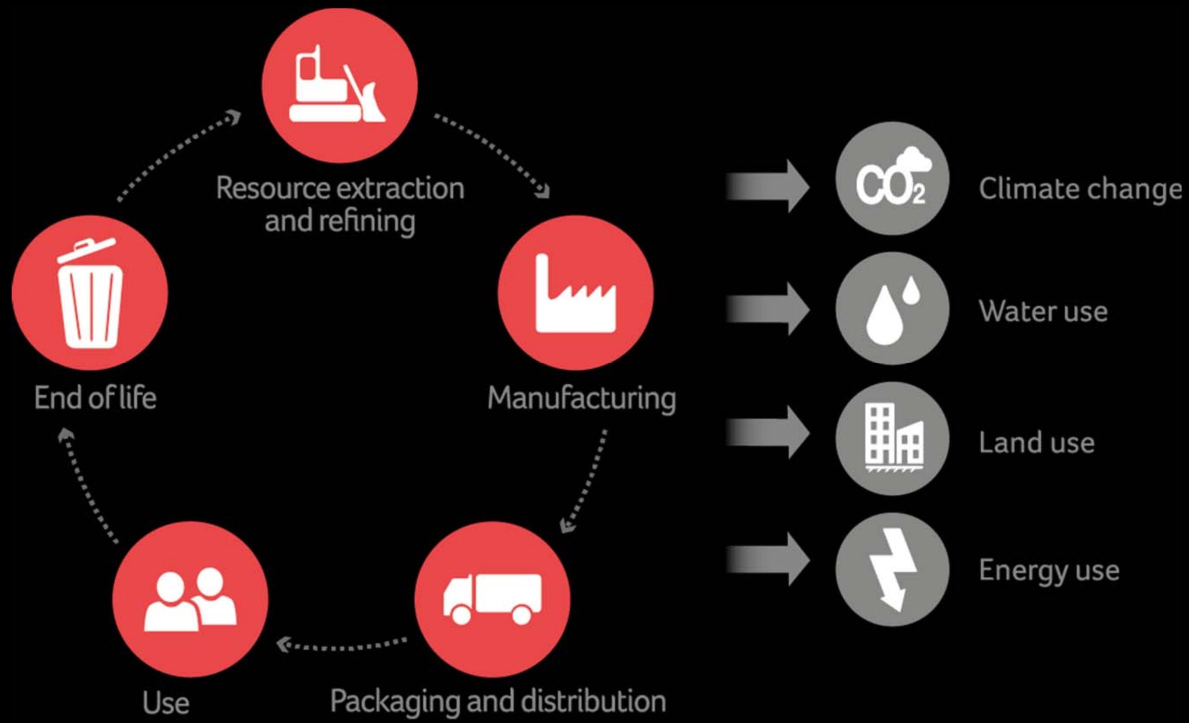




Biodegradability tests: significant amount of biogas was obtained from WaF and WaW, along with reduced COD values.

UASB assay: while lower methane yield was obtained due to low HRT (40 h and 80h), this study showed the feasibility of using AD for the valorization of the wastewaters from the BC fermentation process.

LIFE CYCLE ASSESSMENT



environmental,

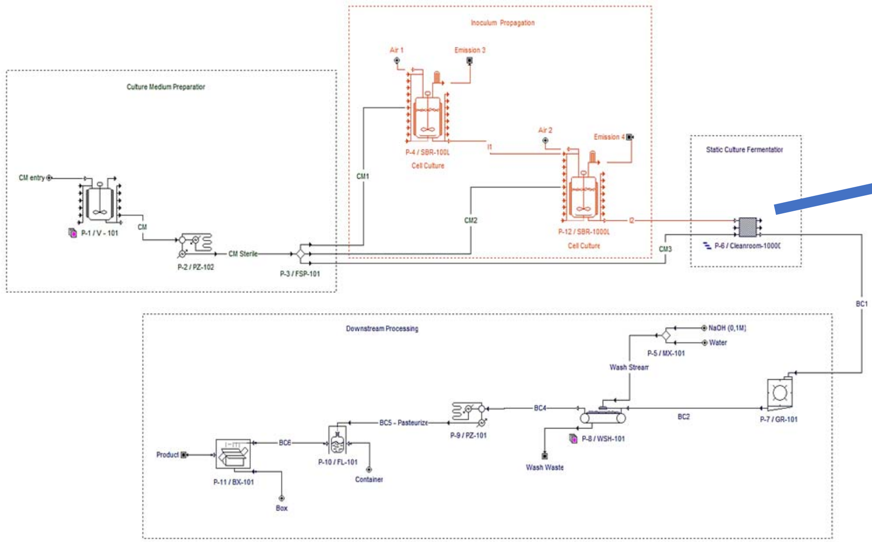
health and

resource depletion

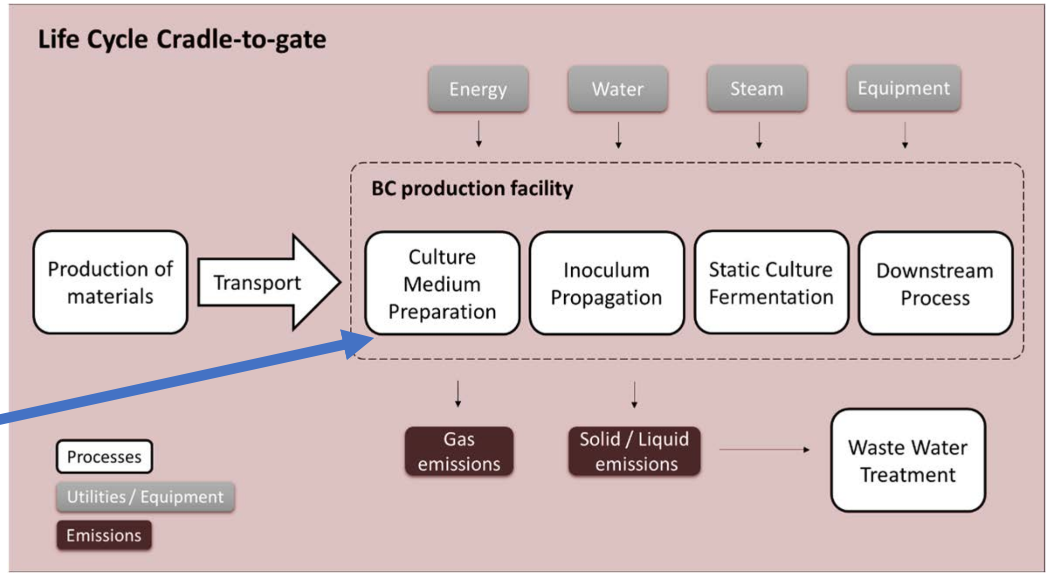
BACTERIAL CELLULOSE

Methodology: ISO 14040 and 14044

- Description of the BC production process
- Goal and scope definition and description of system boundaries
- Inventory Analysis
- Impact Assessment



Functional unit: 1 kg of BC (bone-dry mass), equivalent to 139 kg of final (wet) product



Impact Assessment

Gabi Pro software
ReCiPe 2016

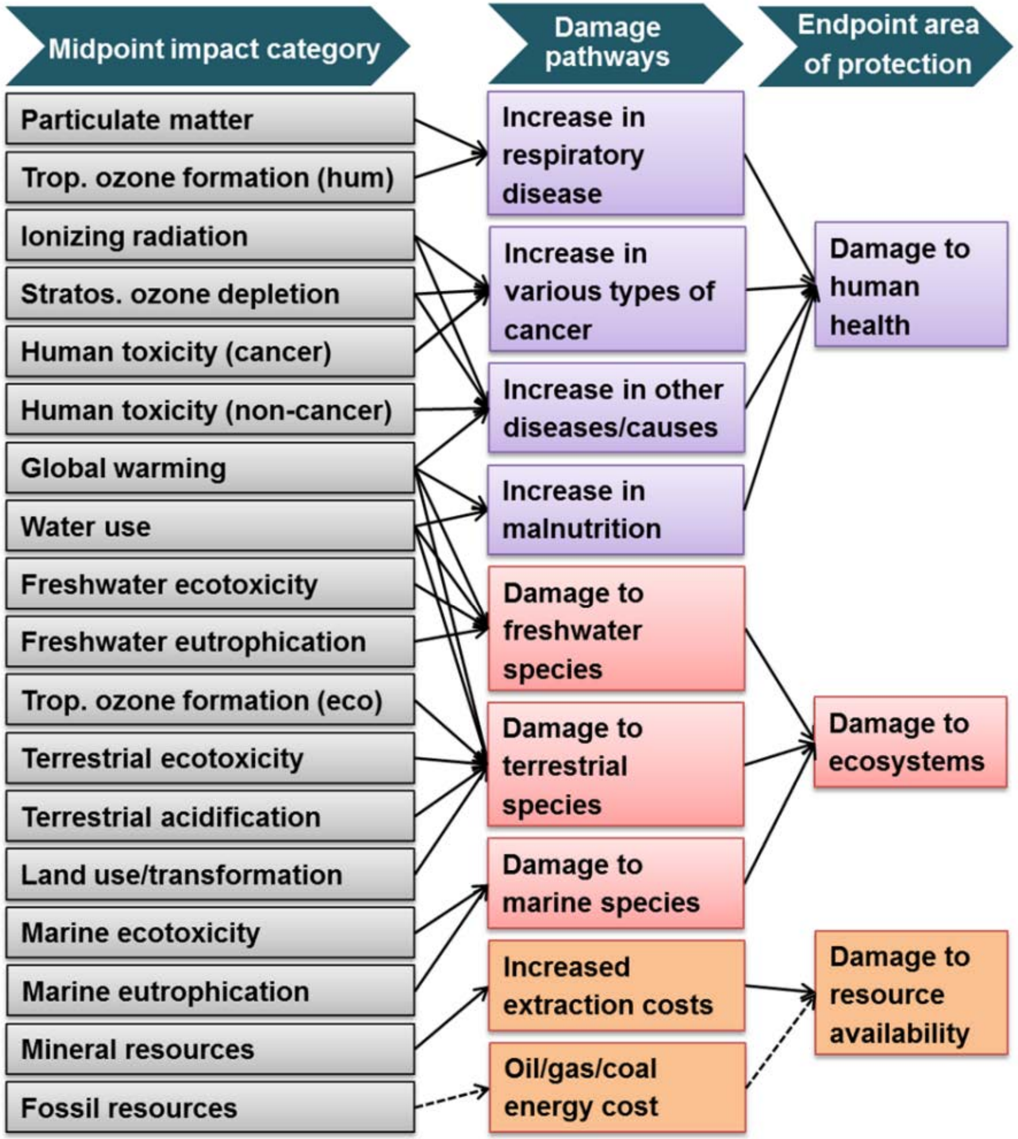
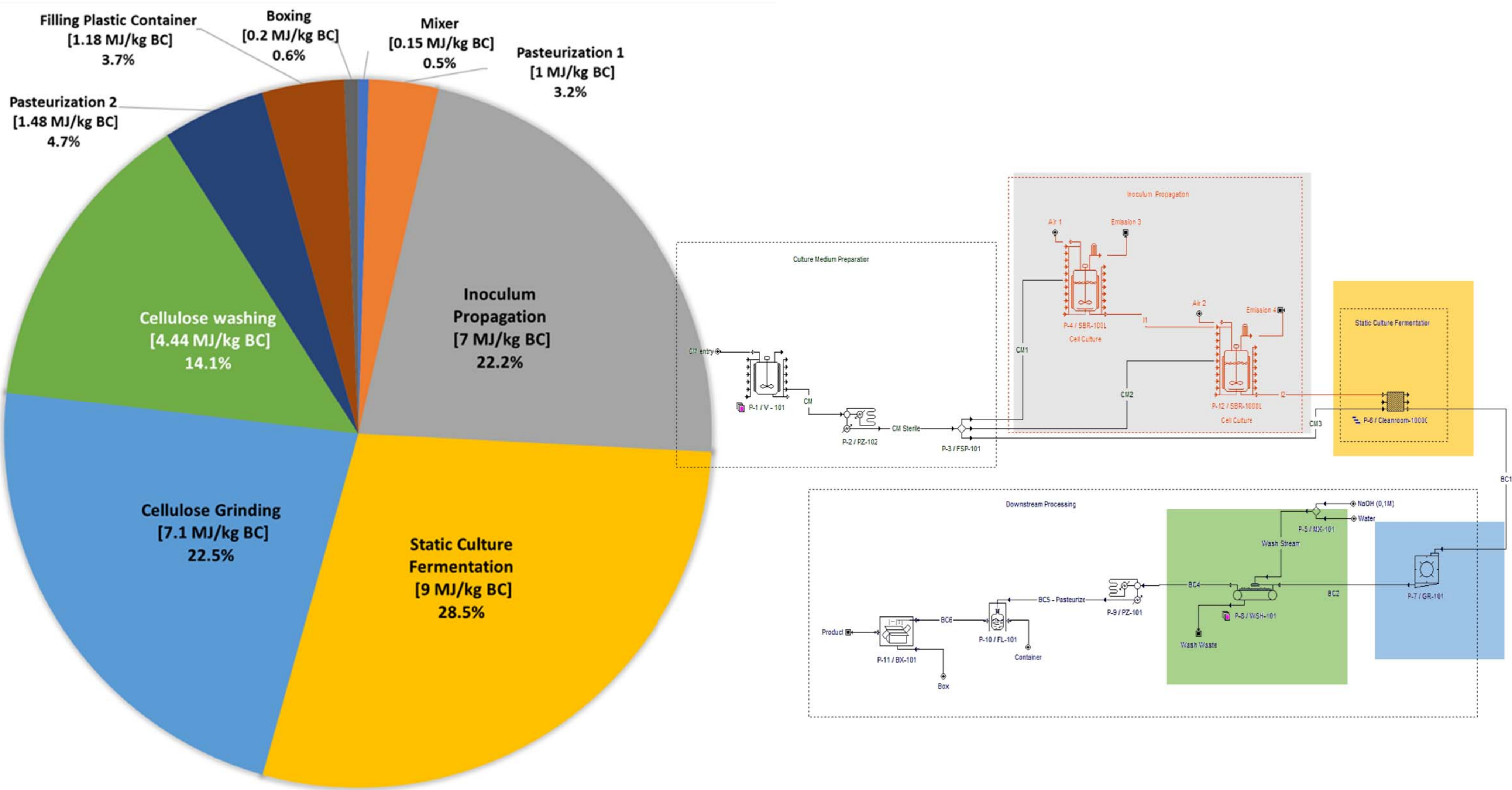


Figure 1.1. Overview of the impact categories that are covered in the ReCiPe2016 methodology and their relation to the areas of protection.

Mass balance of input (resources) and output (deposited goods and emissions) flows of the BC life cycle (1 kg BC, dry mass).

	Total (kg)	Production of materials (%)	Transport of materials (%)	Culture Medium Preparation (%)	Inoculum Propagation (%)	Stactic Culture Fermentation (%)	Downstream Process (%)	Wastewater treatment (%)
Resources (Total)	38,863.9	45.9	0.0	3.8	8.5	9.9	19.9	12.0
Energy resources	7.311	58.3	1.4	5.0	4.0	12.6	14.2	4.4
Material resources	38,856.5	45.9	0.0	3.8	8.5	9.9	19.9	12.0
Non renewable elements	0.4	81.9	0.0	5.7	0.6	0.9	3.1	7,8
Non renewable resources	20.6	31.8	0.1	8.1	5.6	11.0	19.4	24,1
Renewable resources	38,835.6	45.9	0.0	3.8	8.5	9.9	19.9	12,0
Water	36,129.8	49.3	0.0	4.0	9.1	10.7	21,3	5,7
Other renewable resources	2,705.8	0.8	0.0	0.8	0.3	0.5	1,5	96,1
Deposited goods	13.5	25.3	0.1	7.7	6.8	7.6	19.2	33.4
Emissions to air	2,96.0	29.9	0.1	5.4	11.2	18.2	27.2	8.1
Emissions to fresh water	35,861	47.9	0.0	1.6	8.8	10.6	18.1	12.9
Analytical measures to fresh water	0.2	39.3	0.0	0.5	0.9	1.1	2.2	56,0
ecoinvent long-term to fresh water	0.4	100.0	0.0	0.0	0.0	0.0	0.0	0,0
Inorganic emissions to fresh water	0.3	73.1	0.2	0.9	1.6	2.1	4.0	18,0
Other emissions to fresh water	35,554.3	47.9	0.0	1.6	8.9	10.7	18.2	12,8
Radioactive emissions to fresh water	305.8	50.3	0.3	2.1	4.2	5.0	10.2	28,0
Emissions to sea water	58.2	21.0	0.0	11.5	5.3	23.4	26.9	11.8
Emission (total)	72,089.7	47.8	0.0	1.7	8.8	10.7	18.2	12.9



Energy consumption for the whole life cycle of BC production. Values are based on the functional unit of 1kg BC dry basis).

Environmental impacts of life cycle of BC using ReCiPe 2016 Midpoint (H) for 1 kg of dried BC, blue bars represent positive values while red bars represent negative values.

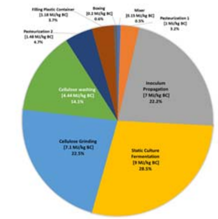
Midpoint Impact category	Units	Total	Production of materials	Transport of materials	Culture Medium Preparation	Inoculum Propagation	Stactic Culture Fementation	Downstream Process	Wastewater treatment
Climate change, default, excl biogenic carbon	[kg CO2 eq.]	16.774	7.3500	0.3200	1.0300	0.8330	2.6700	2.9400	1.6200
Climate change, incl biogenic carbon	[kg CO2 eq.]	16.729	6.4100	0.3200	1.0300	0.8310	2.6700	2.9400	2.5200
Fine Particulate Matter Formation	[kg PM2.5 eq.]	0.016	0.0123	0.0004	0.0003	0.0003	0.0008	0.0009	0.0006
Fossil depletion	[kg oil eq.]	6.565	3.7850	0.1050	0.3610	0.2340	0.8880	0.9380	0.2560
Freshwater Consumption	[m3]	0.470	0.7740	0.0000	0.8590	0.1170	0.0329	1.1800	-2.5000
Freshwater ecotoxicity	[kg 1,4 DB eq.]	0.086	0.0600	0.0000	0.0002	0.0001	0.0001	0.0003	0.0258
Freshwater Eutrophication	[kg P eq.]	0.004	0.0024	0.0000	0.0000	0.0000	0.0000	0.0000	0.0016
Human toxicity, cancer	[kg 1,4-DB eq.]	0.826	0.6930	0.0000	0.0013	0.0007	0.0013	0.0027	0.1280
Human toxicity, non-cancer	[kg 1,4-DB eq.]	13.765	7.6479	0.0021	0.0464	0.0173	0.0170	0.0808	5.9500
Ionizing Radiation	[Bq C-60 eq. to air]	0.342	0.3009	0.0001	0.0016	0.0025	0.0029	0.0066	0.0268
Land use	[Annual crop eq.·y]	0.967	0.6260	0.0000	0.0137	0.0703	0.0842	0.1400	0.0332
Marine ecotoxicity	[kg 1,4-DB eq.]	0.123	0.0856	0.0003	0.0003	0.0002	0.0002	0.0006	0.0353
Marine Eutrophication	[kg N eq.]	0.004	0.0010	0.0000	0.0000	0.0000	0.0000	0.0001	0.0030
Metal depletion	[kg Cu eq.]	0.113	0.0639	0.0000	0.0240	0.0032	0.0012	0.0276	-0.0070
Photochemical Ozone Formation, Ecosystems	[kg NOx eq.]	0.030	0.0175	0.0024	0.0010	0.0011	0.0028	0.0033	0.0021
Photochemical Ozone Formation, Human Health	[kg NOx eq.]	0.029	0.0163	0.0024	0.0010	0.0011	0.0028	0.0032	0.0021
Stratospheric Ozone Depletion	[kg CFC-11 eq.]	0.000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Terrestrial Acidification	[kg SO2 eq.]	0.043	0.0323	0.0010	0.0008	0.0010	0.0027	0.0028	0.0020
Terrestrial Ecotoxicity	[kg 1,4-DB eq.]	15.625	14.2683	0.0317	0.1800	0.1530	0.1870	0.3660	0.3950

Culture medium: Corn syrup production, Disodium phosphate,

Washing BC: Sodium hydroxide,

Plastic bags & Carton production: Polyethylene, Carton production

Fermentation process: Energy consumption



Funcarb group

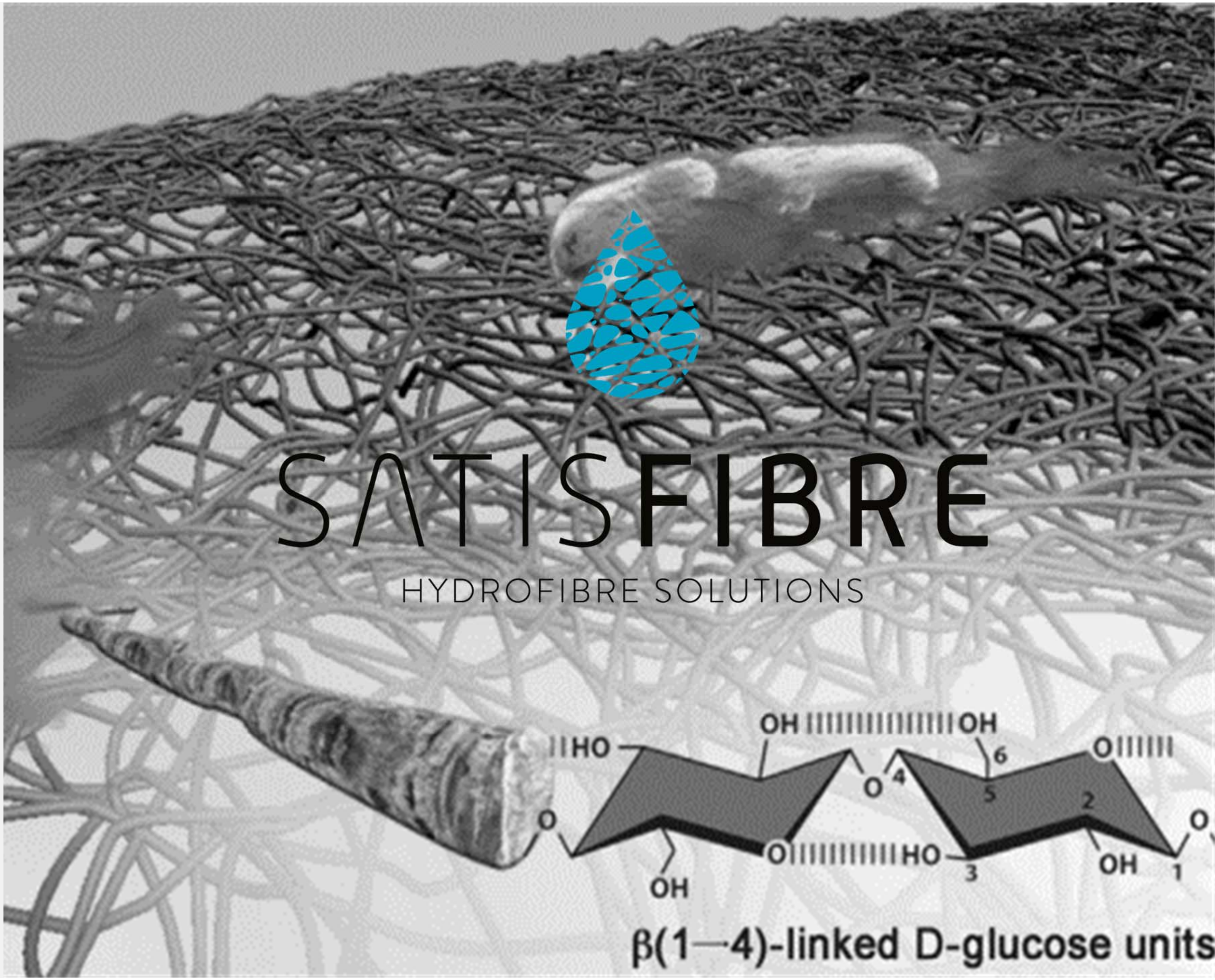
FUNctional andCARBohydrates Nanobiotechnology

Miguel Gama
Associate Professor with Habilitation
fmgama@deb.uminho.pt

Fernando Dourado
Assistant Researcher
fdourado@deb.uminho.pt

Universidade do Minho SPINOFF

CENTRE OF BIOLOGICAL ENGINEERING



2013

LABORATORY

Optimization of Bacterial Cellulose fermentation;

Proof of concept: food & cosmetic formulations contaning BC

2014 – 2018

PILOT SPINPARK

Scale-up of BC fermentation;

Food product formulations contaning BC

Cosmetic formulations containing BC

R&D

PROJECT

Design of the industrial BC production facility

Regulatory approval of BC as a novel food ingredientet for human consumption in EU

Regulatory assesment of BC for cosmetic applications in EU

2020

FUTURE DIRECTIONS

Exploring several paths for the comercial exploitation of the BC production technology & products

THE NAVIGATOR COMPANY

Navigator Products & Technologies, S.A.

Intellectual property

inpi instituto nacional da propriedade industrial

DESCRIPTION

BACTERIAL CELLULOSE COMPOSITES, METHODS AND USES THEREOF

DESCRIPTION

BACTERIAL CELLULOSE FORMULATIONS, METHODS AND USES THEREOF

efsa

European Food Safety Authority

BUILD - Bacterial cellulose leather

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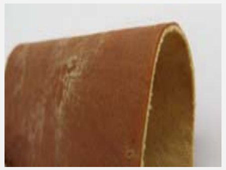
KYAIA FLY LONDON ctcp centro tecnológico do calçado de portugal



FCT FACULDADE DE CIÊNCIAS E TECNOLOGIA UNIVERSIDADE NOVA DE LISBOA

Inpactus - Innovative Products and Technologies from Eucalyptus

THE NAVIGATOR COMPANY

KETI Korea Electronics Technology Institute

CRESYN