EBNet
Environmental Biotechnology

An LCA approach to mitigate plastic pollution

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What are microplastics and what are their production rate and sources?

Larger pieces of polymers progressively breakdown into smaller pieces; microplastics are those with the largest dimension of less than 5mm.

In 2019, 368 million tonnes of plastic were produced world-wide.

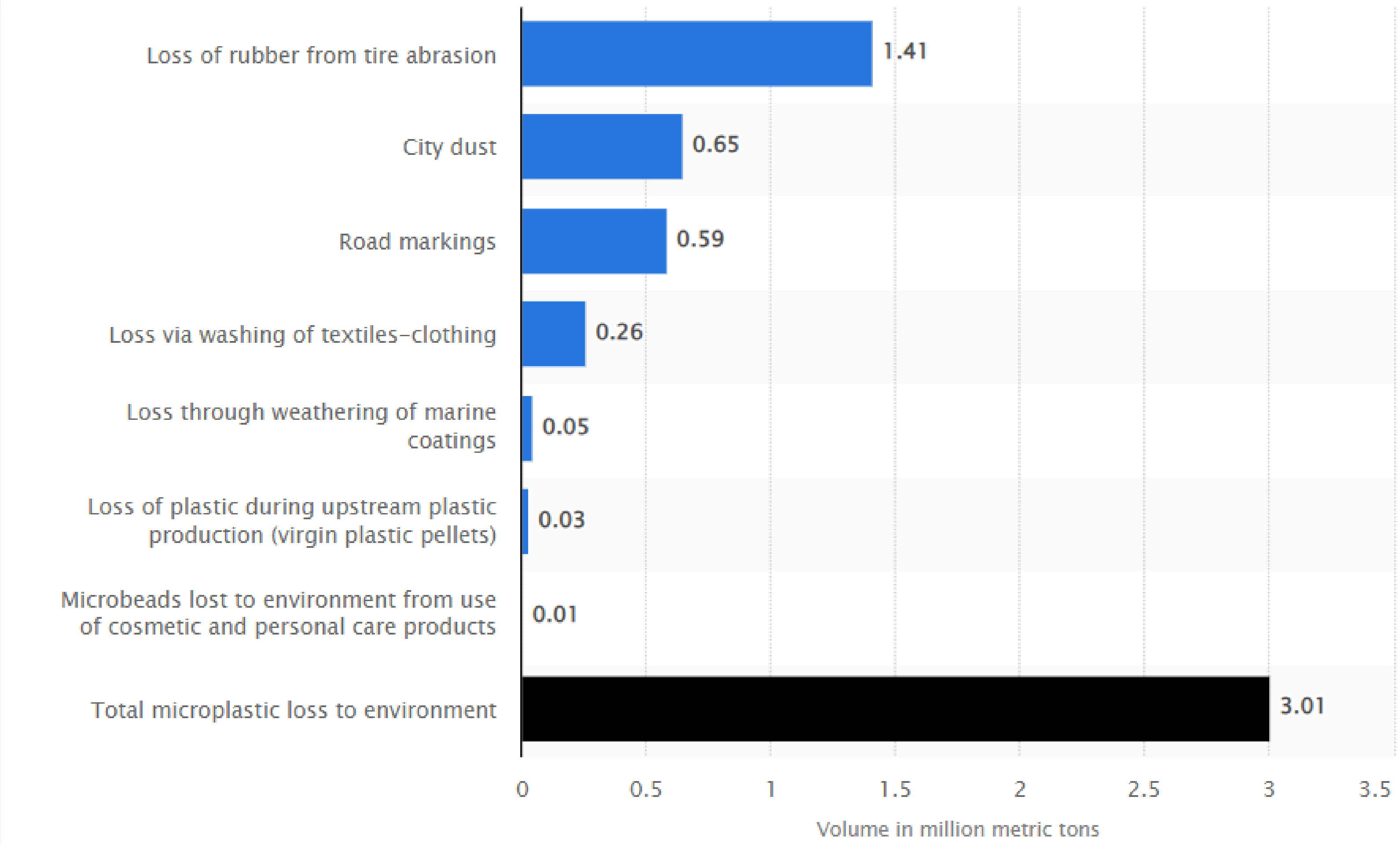
We consume microplastics through air, water, seafood, honey, sugar, beer and salt.

Whitehead, P.G., Bussi, G., Hughes, J.M., Castro-Castellon, A.T., Norling, M.D., Jeffers, E.S., Rampley, C.P., Read, D.S. and Horton, A.A., 2021. Modelling microplastics in the River Thames: sources, sinks and policy implications. *Water*, *13*(6), p.861.

Chemicals & Resources › Plastic & Rubber

Annual volume of microplastics lost to the environment

(in million metric tons)



https://www.statista.com/statistics/1192550/soures-of-microplastics-entering-environment-worldwide/

Most commonly used plastics

	What is it used for?	Next life	Ease of recycling
Polyethylene Terephthalate (PET) 1	Soft drink bottles, food packaging such as punnets	Used to make more PET products	Easy
High Density Polyethylene (HDPE) 2	Milk cartons, cleaning products, yoghurt pots, soap dispensers	Garden furniture, pipes and more milk cartons	Easy
Polyvinyl Chloride (PVC) 3	Pipe fittings, window fittings, thermal insulation, car parts	Used to make more PVC products	Difficult
Low Density Polyethylene (LDPE) 4	Food bags, shopping bags, magazine wrapping	Bin liners, plastic furniture and floor tiles	Manageable
Polypropylene (PP) 5	Margarine tubs, microwave meal trays, fibres and filaments for carpet, wall coverings, vehicle upholstery	Clothing fibres, food containers, speed humps	Easy
Polystyrene (PS) 6	Some yoghurt pots, takeaway boxes, plastic cutlery, protective packaging, insulation	As more packaging	Difficult
Other 7	This includes other forms of plastic including composites, such as salad bags and crisp packets	Goes to landfill	Very difficult

Recyclable

Recyclable at specialist points

Not easily recyclable

Which?

Microplastic extraction methods

Size separation

Density separation

Visual sorting

NaCl flotation

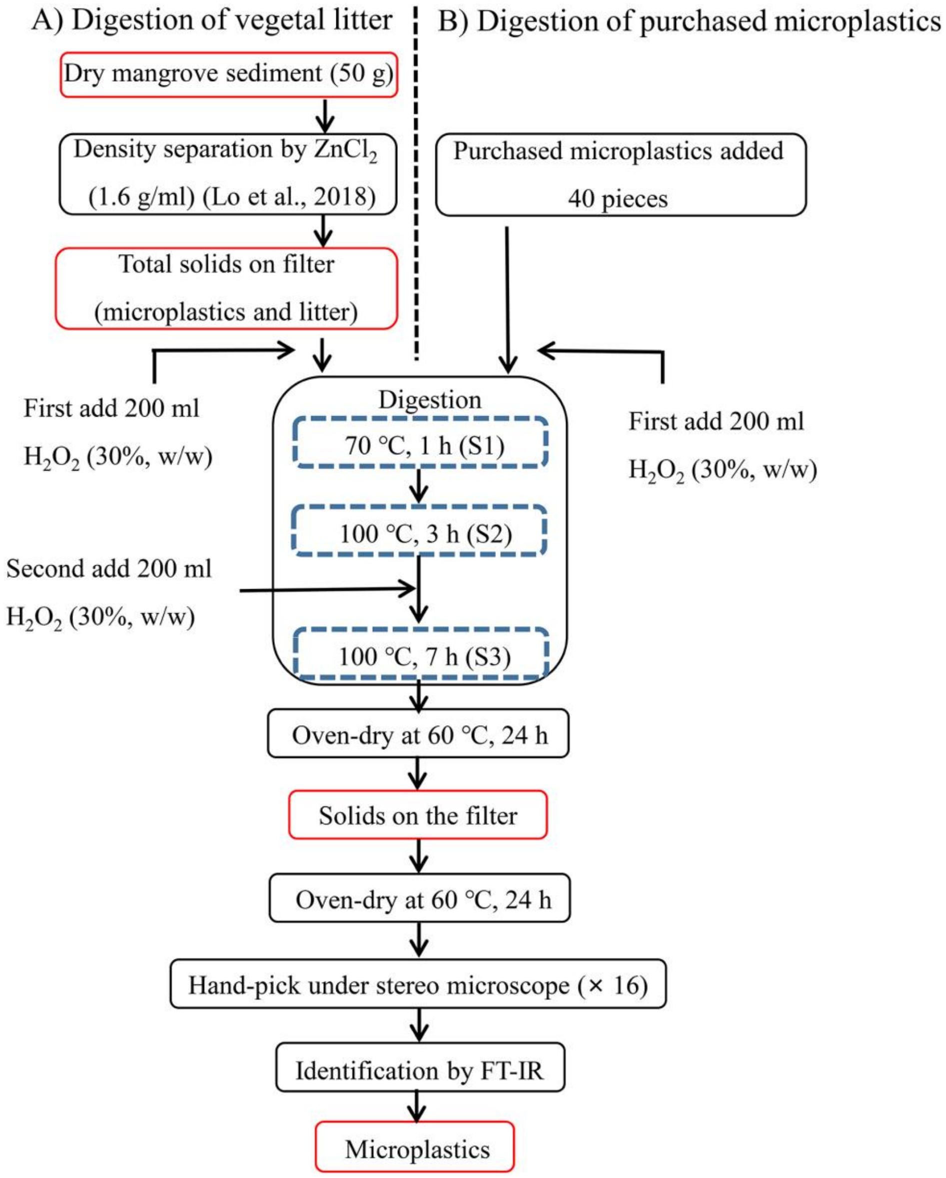
HCl, H_2O_2 and $ZnCl_2$

Digestion

Chemical dissolution and alteration

Fenton oxidation (hydrogen peroxide concentration of 250 g/L (30% w/w, diluted with ultrapure water to the desired concentration) and an iron (II) sulphate concentration of 2.5 g/L)

Basic Piranha oxidation (hydrogen peroxide concentration of 125 g/L (30% w/w, diluted with ultrapure water to the desired concentration) and an ammonium hydroxide concentration of 105 g/L (25% w/w))



Ball, H.; Cross, R.; Grove, E.; Horton, A.; Johnson, A.; Jürgens, M.; Read, D.; Svendsen, C. Sink to River—River to Tap. In A Review of Potential Risks from Nanoparticles and Microplastics; UKWIR: London, UK, 2020

Whitehead, P.G., Bussi, G., Hughes, J.M., Castro-Castellon, A.T., Norling, M.D., Jeffers, E.S., Rampley, C.P., Read, D.S. and Horton, A.A., 2021. Modelling microplastics in the River Thames: sources, sinks and policy implications. *Water*, *13*(6), p.861.

Pfohl, P., Roth, C., Meyer, L., Heinemeyer, U., Gruendling, T., Lang, C., Nestle, N., Hofmann, T., Wohlleben, W. and Jessl, S., 2021. Microplastic extraction protocols can impact the polymer structure. *Microplastics and Nanoplastics*, *1*(1), pp.1-13.

Duan, J., Han, J., Zhou, H., Lau, Y.L., An, W., Wei, P., Cheung, S.G., Yang, Y. and Tam, N.F.Y., 2020. Development of a digestion method for determining microplastic pollution in vegetal-rich clayey mangrove sediments. *Science of The Total Environment*, *707*, p.136030.

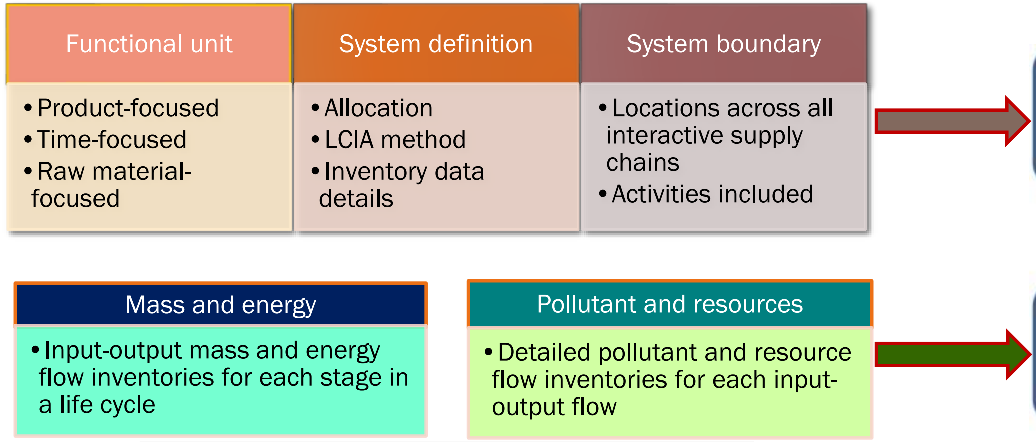


Table 4.23(d) *Units for various impact characterizations under ReCiPe.*

Impact Characterization	Accepted Unit
Climate change	kg CO_2 equivalent
Terrestrial acidification	kg SO_2 equivalent
Freshwater eutrophication potential	kg P equivalent
Ozone depletion potential	kg CFC-11 equivalent
Fossil depletion	kg oil equivalent
Freshwater ecotoxicity	kg DCB equivalent
Ionizing radiation	kg U235 equivalent
Marine ecotoxicity	kg DCB equivalent
Marine eutrophication	kg N equivalent
Metal depletion	kg Fe equivalent
Natural land transformation	m^2
Particulate matter formation	kg PM10 equivalent
Photochemical oxidant formation	kg NMVOC equivalent
Terrestrial ecotoxicity	kg DCB equivalent
Water depletion	m^3

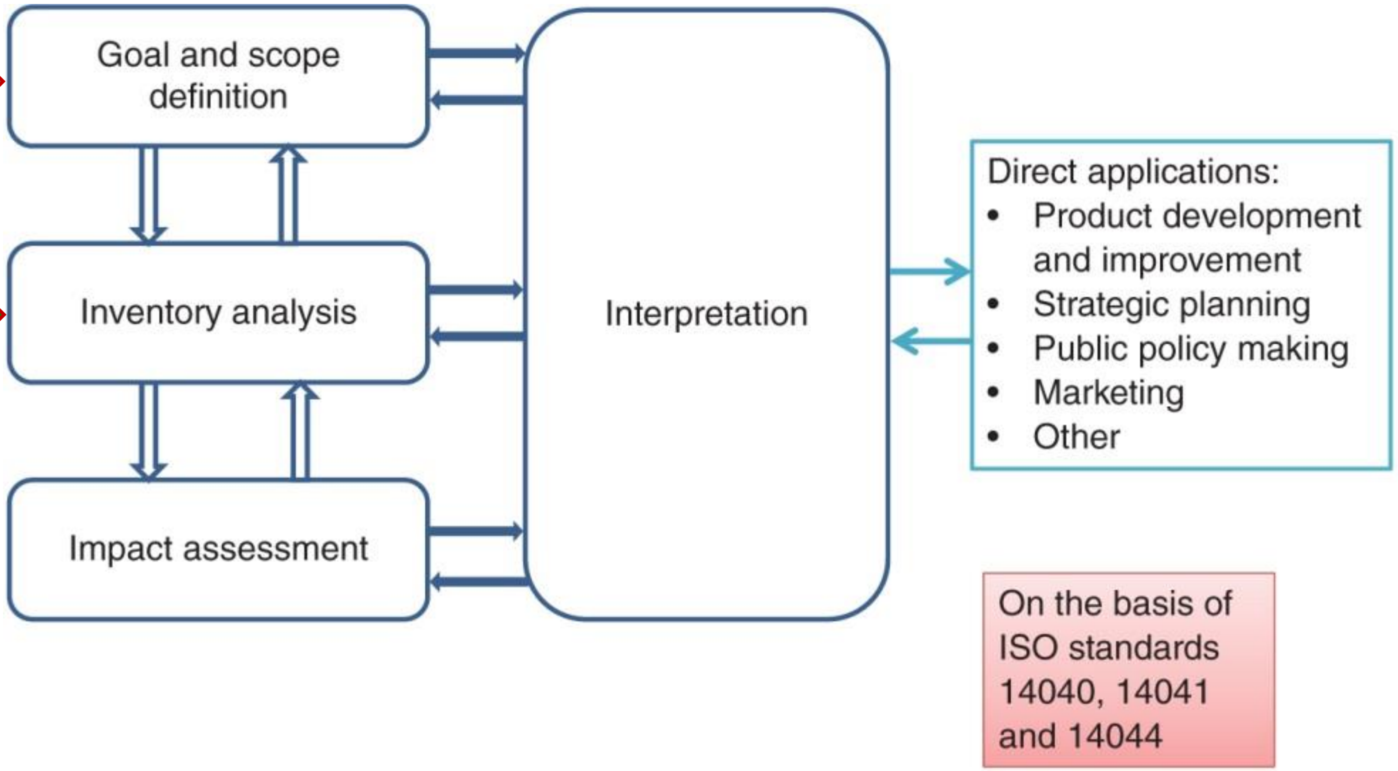
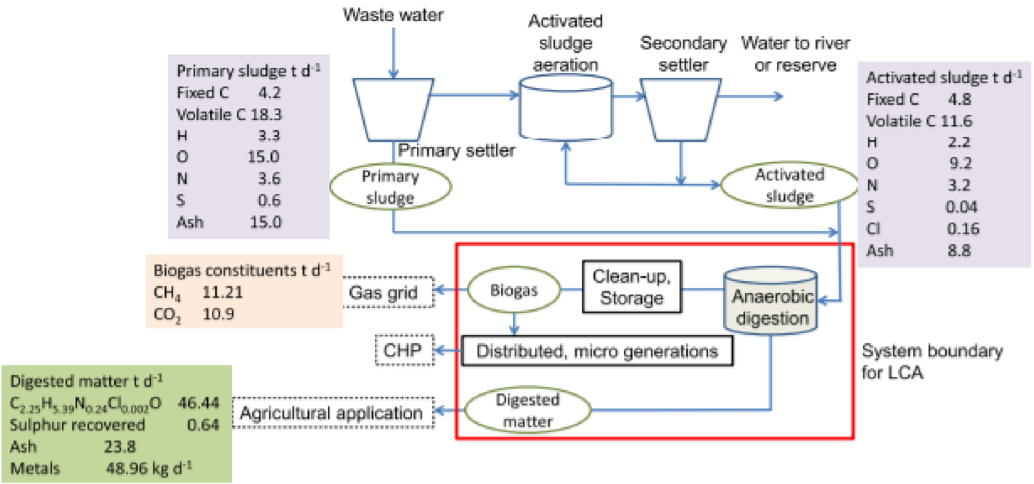


Figure 4.5 *LCA study stages*[4–6].

Biorefineries and Chemical Processes: Design, Integration and Sustainability Analysis, First Edition.
Jhuma Sadhukhan, Kok Siew Ng and Elias Martinez Hernandez.

Companion Website: http://www.wiley.com/go/sadhukhan/biorefineries



Ash content	Weight %	Molar mass	Density g cm^{-3}
Silicon oxide (SiO_2)	14-34	60.08	2.65
Aluminium oxide (Al_2O_3)	6-23	102	3.95
Iron oxide (Fe_2O_3)	5-9	159.7	5.24
Titanium oxide (TiO2)	1-2	79.9	4.23
Manganese oxide (Mn_3O_4)	0.1	228.8	4.86
Calcium oxide (CaO)	10-20	56	3.35
Magnesium oxide (MgO)	2-6	40	3.58
Sodium oxide (Na_2O)	0.5-1.5	62	2.27
Potassium oxide (K_2O)	1-7	94	2.35
Phosphorus pentoxide (P_2O_5)	15-40	283.9	2.39

Metal	Mass mg kg^{-1} sludge	Molar mass	Molar volume cm^3 mol^{-1}
Cadmium (Cd)	0.6	112	13
Zinc (Zn)	220	65	9.16
Vanadium (V)	7. 5	51	8.34
Lead (Pb)	47	207	18.3
Copper (Cu)	166	63.5	7.12
Chromium (Cr)	13	52	7.28
Nickel (Ni)	14	58.7	6.59
Cobalt (Co)	1.9	58.9	6.62
Thallium (Tl)	0.05	204	17.2
Arsenic (As)	0.10	74.9	13.1
Mercury (Hg)	0.4	200.6	14.8
Boron (B)	14	10.8	4.39
Molybdenum (Mo)	5	96	9.33

Fig. 1. Waste water treatment plant configuration and reconciled operational data.

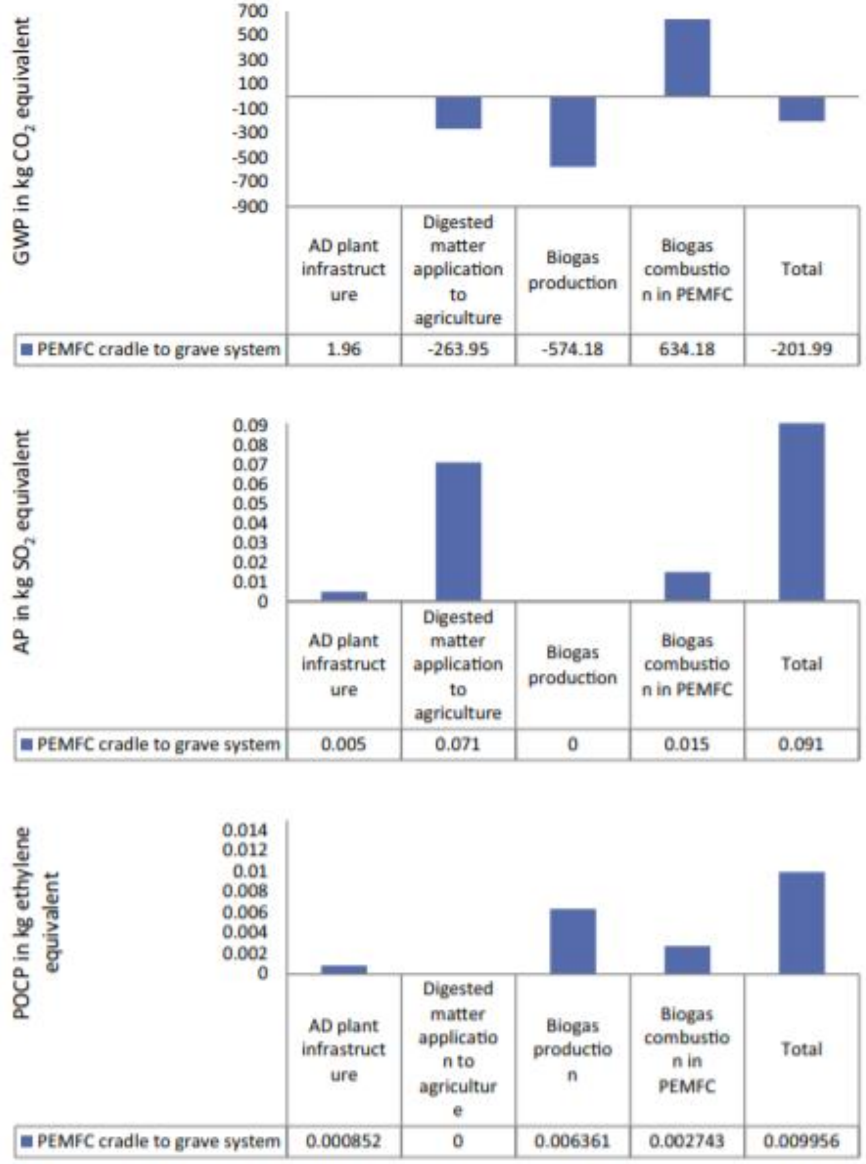


Fig. 4. GWP, AP and POCP: comparison between individual processes in the PEMFC cradle to grave micro-generation system on the basis of 11,340 MJ biogas production and processing. The *x*-axis shows the processing steps, thus the hotspot in each category.

Various CHP generation process technologies for electricity and heat generations from 11,340 MJ of biogas are shown as follows.

1. Proton exchange membrane fuel cell 2 kWe (*PEM FC*): Electricity: 3628.8 MJ; Heat: 6237 MJ.
2. Solid oxide fuel cell 125 kWe (*SOFC*): Electricity: 5330 MJ; Heat: 3742 MJ.
3. SOFC-GT fuel cell 180 kWe (*SOFC-GT*): Electricity: 6577 MJ; Heat: 2495 MJ.
4. Micro gas turbine 100 kWe (*Micro GT*): Electricity: 3402 MJ; Heat: 5103 MJ.

Processing of 11,340 MJ of natural gas through the following systems into electricity and heat generations was considered.

1. Proton exchange membrane fuel cell 2 kWe (*PEM FC*): Electricity: 4205 MJ; Heat: 2825 MJ.
2. Solid oxide fuel cell 125 kWe (*SOFC*): Electricity: 5962 MJ; Heat: 3643 MJ.
3. SOFC-GT fuel cell 180 kWe (*SOFC-GT*): Electricity: 6997 MJ; Heat: 3093 MJ.
4. Micro gas turbine 100 kWe (*Micro GT*): Electricity: 4173 MJ; Heat: 5226 MJ.

Sadhukhan, J., 2014. Distributed and micro-generation from biogas and agricultural application of sewage sludge: Comparative environmental performance analysis using life cycle approaches. *Applied Energy*, *122*, pp.196-206.

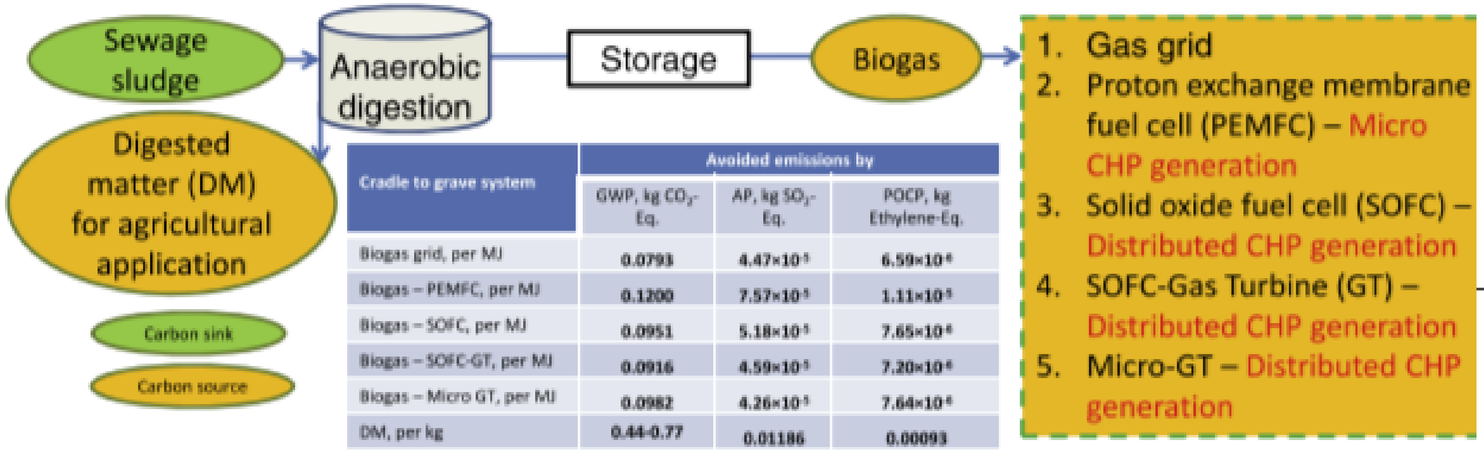


Fig. 5. Summary of environmental performance comparison results of sewage sludge products.

	GWP kg CO_2-equivalent/MJ	AP kg SO_2-equivalent/MJ	POCP kg ethylene-equivalent/MJ
Biogas to grid system	−0.0737	6.70×10^{-6}	6.36×10^{-7}
Natural gas to grid system	0.0056	5.14×10^{-5}	7.23×10^{-6}
Avoided emissions (grid system)	**0.0793**	$\mathbf{4.47 \times 10^{-5}}$	$\mathbf{6.59 \times 10^{-6}}$
Biogas-micro generation (PEM FC based)	−0.0205	9.22×10^{-6}	1.01×10^{-6}
Natural gas-micro generation (PEM FC based)	0.0995	8.49×10^{-5}	1.21×10^{-5}
Avoided emissions (PEM FC based microgen)	**0.1200**	$\mathbf{7.57 \times 10^{-5}}$	$\mathbf{1.11 \times 10^{-5}}$
Biogas-distributed generation (SOFC based)	−0.0223	1.08×10^{-5}	1.30×10^{-6}
Natural gas-distributed generation (SOFC based)	0.0728	6.26×10^{-5}	8.95×10^{-6}
Avoided emissions (SOFC based distributed gen)	**0.0951**	$\mathbf{5.18 \times 10^{-5}}$	$\mathbf{7.65 \times 10^{-6}}$
Biogas-distributed generation (SOFC-GT based)	−0.0223	1.87×10^{-5}	1.62×10^{-6}
Natural gas-distributed generation (SOFC-GT based)	0.0693	6.46×10^{-5}	8.82×10^{-6}
Avoided emissions (SOFC-GT based distributed gen)	**0.0916**	$\mathbf{4.59 \times 10^{-5}}$	$\mathbf{7.20 \times 10^{-6}}$
Biogas-distributed generation (Micro GT based)	−0.0234	3.95×10^{-5}	3.42×10^{-6}
Natural gas-distributed generation (Micro GT based)	0.0748	8.21×10^{-5}	1.11×10^{-5}
Avoided emissions (Micro GT based distributed gen)	**0.0982**	$\mathbf{4.26 \times 10^{-5}}$	$\mathbf{7.64 \times 10^{-6}}$

Four projects on plastic or plastic recycling LCA

POLYHYDROXY BUTYRATE SYNTHESIS	MIXED PLASTIC WASTE RECYCLING	RECYCLING OF WASTE PLASTICS FROM HEALTHCARE	NOVEL BIOPOLYMERS
Metabolic pathway and flux analyses Reaction and process engineering Environmental and economic life cycle analyses	Life cycle assessment to decide products, co-products, displacements, allocations, etc.	Experimental design ASTM testing analyses Life cycle assessment Economic analysis	Novel biopolymer formulations and synthesis Mechanical and chemical properties Process engineering Recyclability and supply chain sustainability

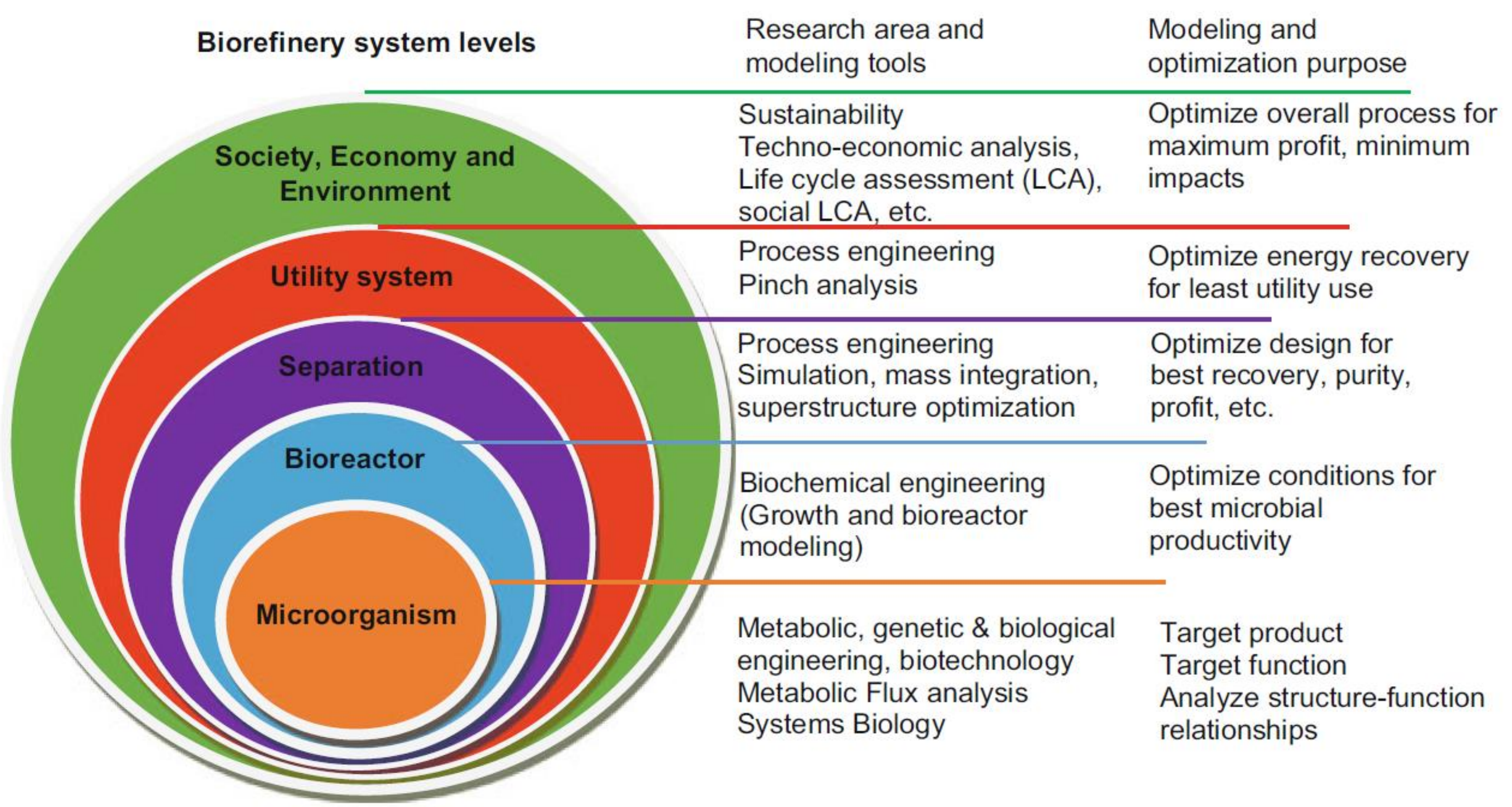


Fig. 14.1 Onion model of biorefinery system and the modeling tools and optimization purposes at each level

Martinez-Hernandez, E., Ng, K.S., Allieri, M.A.A., Anell, J.A.A. and Sadhukhan, J., 2018. Value-added products from wastes using extremophiles in biorefineries: process modeling, simulation, and optimization tools. In *Extremophilic microbial processing of lignocellulosic feedstocks to biofuels, value-added products, and usable power* (pp. 275-300). Springer, Cham.

Martinez-Hernandez, E., Ng, K.S., Allieri, M.A.A., Anell, J.A.A. and Sadhukhan, J., 2018. Value-added products from wastes using extremophiles in biorefineries: process modeling, simulation, and optimization tools. In *Extremophilic microbial processing of lignocellulosic feedstocks to biofuels, value-added products, and usable power* (pp. 275-300). Springer, Cham.

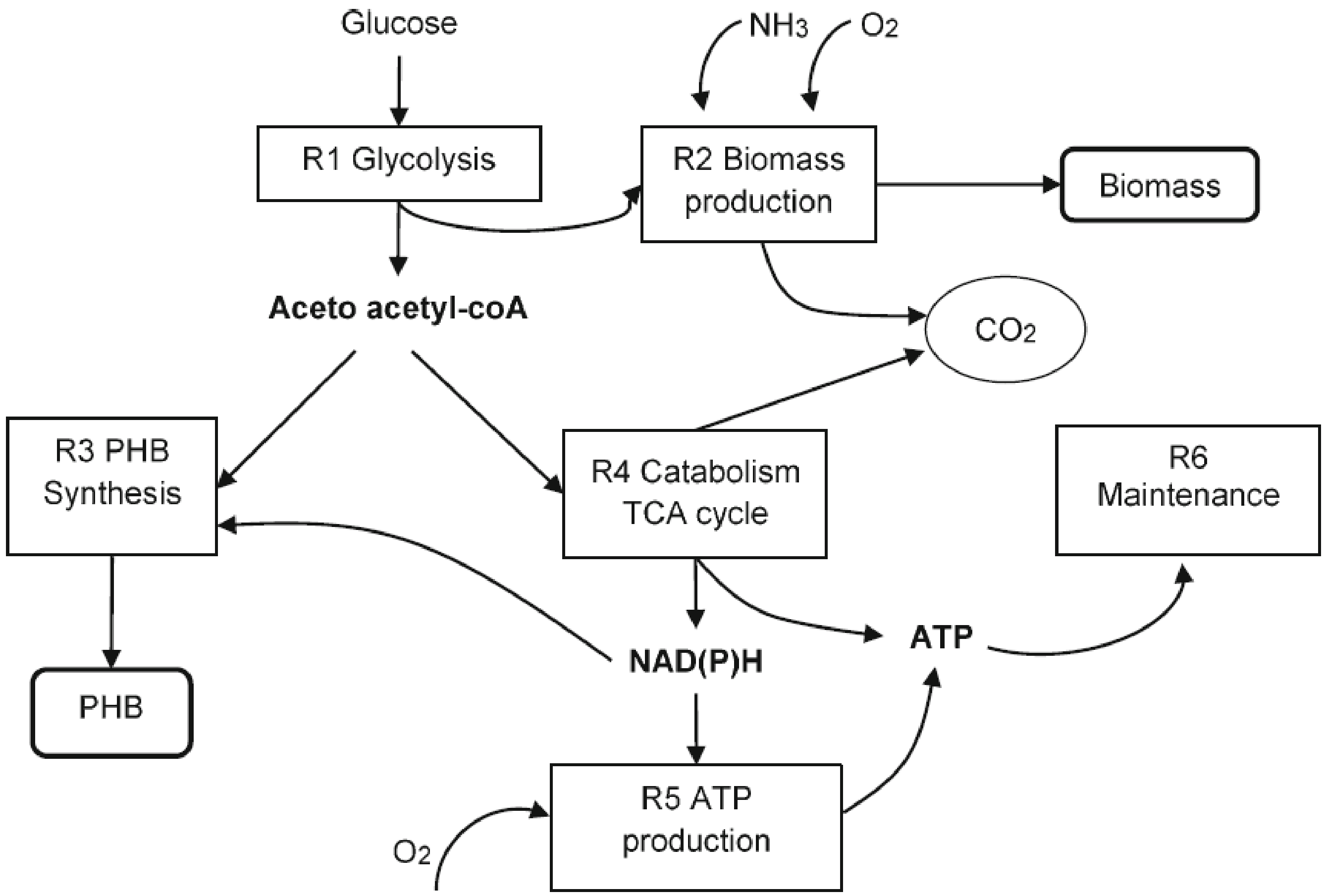


Fig. 14.3 Simplified metabolic model for PHB production from *Halomonas* sp.

Table 14.3 Metabolic model for PHB production

Reaction	Reaction equation
R1 Glucose conversion to acetyl-CoA	$C_6H_{12}O_6 \rightarrow$ AcetylCoA + 2NAD(P)H + 0.5ATP + CO_2
R2 Biomass production (net reaction from glucose via acetyl-CoA)	$(1 + a)C_6H_{12}O_6 + \frac{1}{5}NH_3 + \left(\frac{2a-1}{4}\right)O_2 \rightarrow CH_{1.74}O_{0.46}N_{0.19} + aCO_2$
R3 PHB synthesis from acetyl-CoA	2AcetylCoA + NAD(P)H + 0.5ATP $\rightarrow$ PHB
R4 Acetyl-CoA catabolism in the TCA cycle	AcetylCoA $\rightarrow$ 4NAD(P)H + ATP + $2CO_2$
R5 ATP production	NAD(P)H + $0.5O_2 \rightarrow \delta$ATP
R6 ATP use for maintenance (nongrowth associated)	$-ATP = 0$

Martinez-Hernandez, E., Ng, K.S., Allieri, M.A.A., Anell, J.A.A. and Sadhukhan, J., 2018. Value-added products from wastes using extremophiles in biorefineries: process modeling, simulation, and optimization tools. In *Extremophilic microbial processing of lignocellulosic feedstocks to biofuels, value-added products, and usable power* (pp. 275-300). Springer, Cham.

Case A: dilution rate $D = 0.1$ for maximum bioreactor productivity (Sect. 14.3.2.2). The PHB yield in the bioreactor was 10.8%, the glucose conversion was 95.3%, and the PHB content in biomass was 20% with a productivity of 0.54 g L^{-1} h^{-1}. The overall PHB yield in respect to bagasse input was 2.1%.

Case B: dilution rate $D = 0.01$ for high PHB yield in the bioreactor = 62%. The glucose conversion was 99.7%, and the PHB content in biomass was 71.4% with a productivity of 0.31 g L^{-1} h^{-1}. The overall PHB in respect to bagasse input was 11.9%. This case includes a combined heat and power (CHP) plant from solid residues.

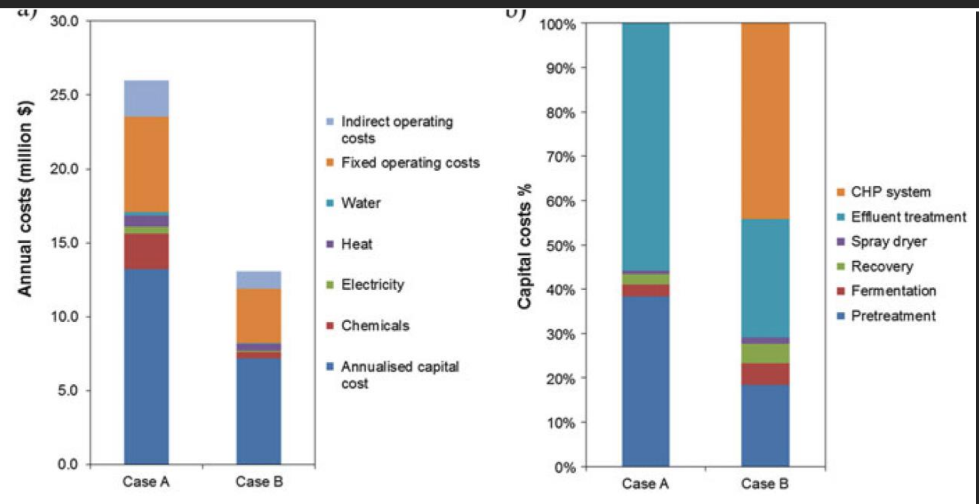


Fig. 14.8 (**a**) Annual operating cost and (**b**) capital cost contribution by various sections of the PHB production process for case A (low yield and no CHP plant) and case B (high yield and with CHP plant)

Table 14.5 Inlet and outlet raw material and energy flowrates of the system, for which inventory data were extracted from Ecoinvent 3.0, for cases A and B

Per kg PHB production	Case A (low yield, no CHP)	Case B (high yield, CHP)
Direct emission from the plant (i.e., CO_2 emission from the fermenter), kg CO_2	0.2125	0.2125
Quantity of raw materials causing indirect impacts of the plant		
Heat from combustion of natural gas, MJ	58.7791	
Sodium hydroxide, kg	2.2844	0.3977
Grid electricity, MJ	5.8950	
SDS, kg	0.5197	0.0521
Sodium chloride, kg	1.1434	0.1285
Sulfuric acid, kg	0.2798	0.0487
Make-up water, kg	131.7748	15.5924
Embedded or captured CO_2 in PHB, kg CO_2	−2.0465	−2.0465

Table 14.6 Primary impacts, for which considerable differences between case B with high-yield and on-site CHP generation and equivalent fossil-based polymer production system exist

Per kg polymer production	Case B: PHB production with CHP generation	Fossil-based equivalent polymer production	Savings by biopolymer production system	% savings by biopolymer
Acidification potential, kg SO_2 equivalent	0.0032	0.0191	0.0159	83.4846
Eutrophication potential, kg phosphate equivalent	0.0016	0.0137	0.0121	88.2027
Freshwater ecotoxicity potential, kg DCB equivalent	0.2814	1.1807	0.8993	76.1698
GWP, kg CO_2 equivalent	−1.3382	7.5146	8.8528	117.8074
Human toxicity potential, kg DCB equivalent	0.3856	7.3761	6.9906	94.7726
Marine ecotoxicity potential, kg DCB equivalent	833.6787	3489.2043	2655.5256	76.1069
Urban smog, kg ethylene equivalent	0.0002	0.0042	0.0040	95.5579
Terrestrial ecotoxicity potential, kg DCB equivalent	0.0121	0.0534	0.0413	77.3540
DCB: 1,4-dichlorobenzene				

Martinez-Hernandez, E., Ng, K.S., Allieri, M.A.A., Anell, J.A.A. and Sadhukhan, J., 2018. Value-added products from wastes using extremophiles in biorefineries: process modeling, simulation, and optimization tools. In *Extremophilic microbial processing of lignocellulosic feedstocks to biofuels, value-added products, and usable power* (pp. 275-300). Springer, Cham.

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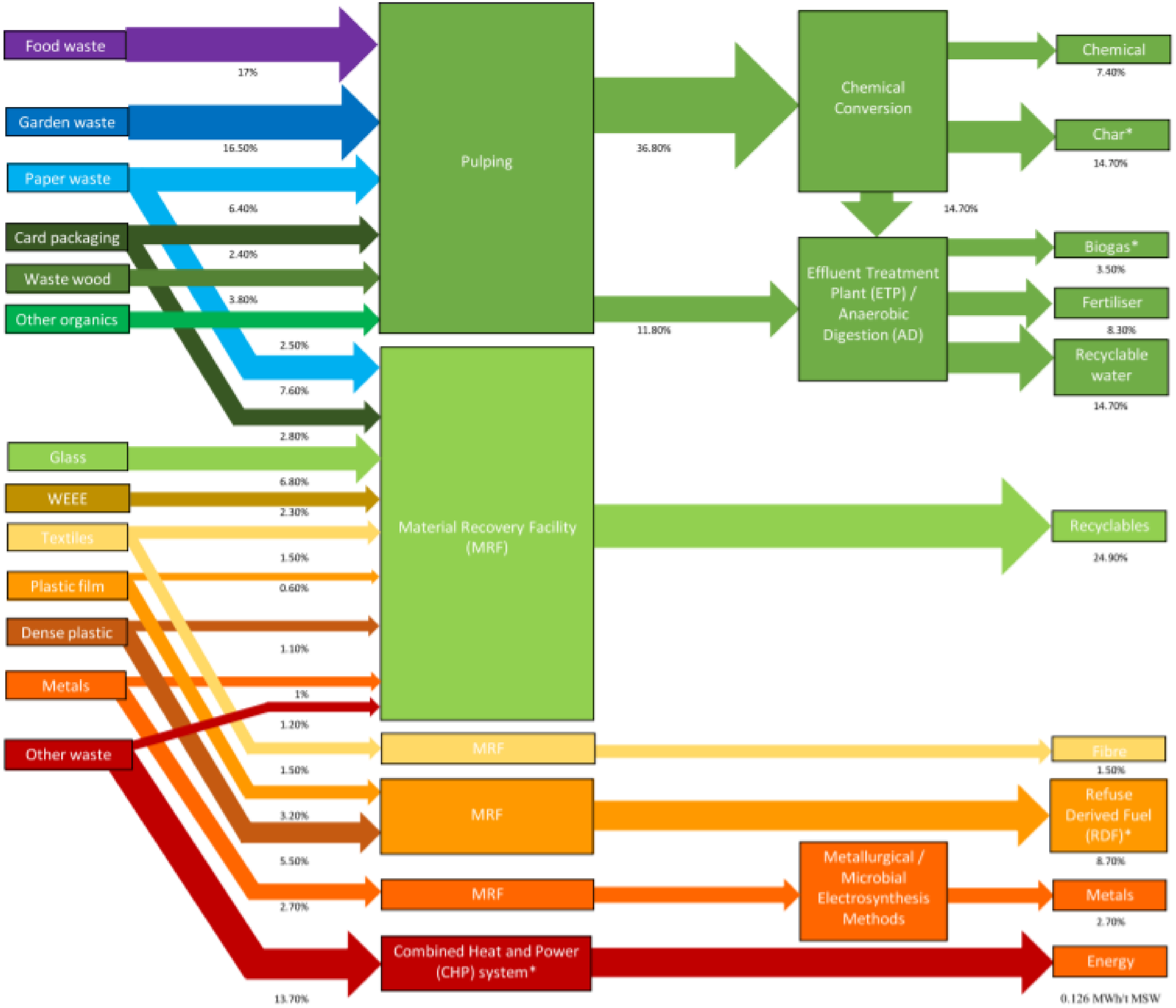
J. Sadhukhan, E. Martinez-Hernandez / Bioresource Technology 243 (2017) 135–146



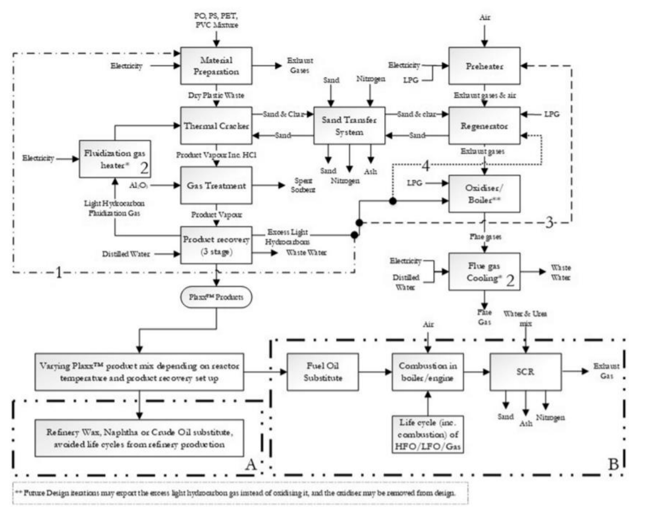


Fig. 2. Initial and modified designs for the RT7000 commercial plant (Recycling Technologies Ltd, 2017) – Numbers 1–4 represent changes to the initial design, discussed in Table 6. A and B show the system expansions for recycling and fuel applications respectively.

Gear, M., Sadhukhan, J., Thorpe, R., Clift, R., Seville, J. and Keast, M., 2018. *Journal of Cleaner Production*, *180*, pp.735-747.

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Contaminated plastics with cell cultures are incinerated to destroy remnants. Our novel technology can recycle these plastics (ASTM complied) at a cost lower than fresh materials. 16 million tonnes of CO_2 equivalent can be saved by our technology compared to incineration of these waste plastics.

Four projects on plastic or plastic recycling LCA

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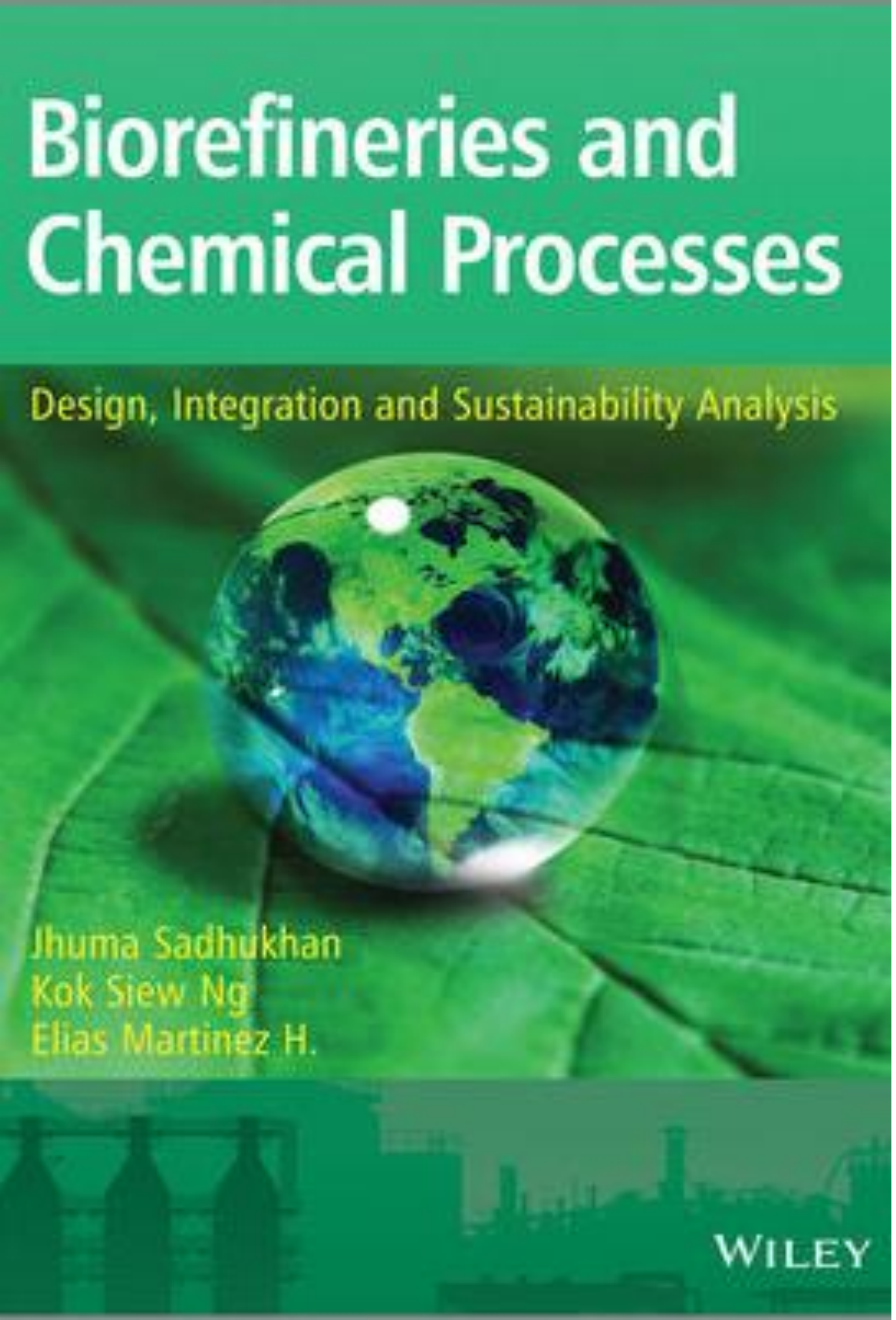
Novel biopolymer formulations and synthesis

Mechanical and chemical properties

Process engineering

Recyclability and supply chain sustainability



Biopolymer (intensive Chapter 12)

https://onlinelibrary.wiley.com/doi/book/10.1002/9781118698129

Is LCA essential to call a system sustainable?

https://byrummonitor.dk/Nyheder/art8553504/Det-er-ulovligt-at-bruge-ordet-b%C3%A6redygtigt-uden-en-livscyklusvurdering

Sadhukhan, J., Sen, S. and Gadkari, S., 2021. The Mathematics of life cycle sustainability assessment. *Journal of Cleaner Production*, *309*, p.127457.

Bjørn, A., Richardson, K. and Hauschild, M.Z., 2019. A framework for development and communication of absolute environmental sustainability assessment methods. *Journal of Industrial Ecology*, *23*(4), pp.838-854.

Lan, K. and Yao, Y., 2021. Dynamic Life Cycle Assessment of Energy Technologies under Different Greenhouse Gas Concentration Pathways. *Environmental science & technology*.

Collaboration opportunities

EBNet Working Group: Process Integration and Sustainability Assessment:

https://ebnet.ac.uk/about/wg-details/wg-lcsa/

CPD LCA module (28 Mar-1 Apr):

https://catalogue.surrey.ac.uk/2021-2/module/ENGM253

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