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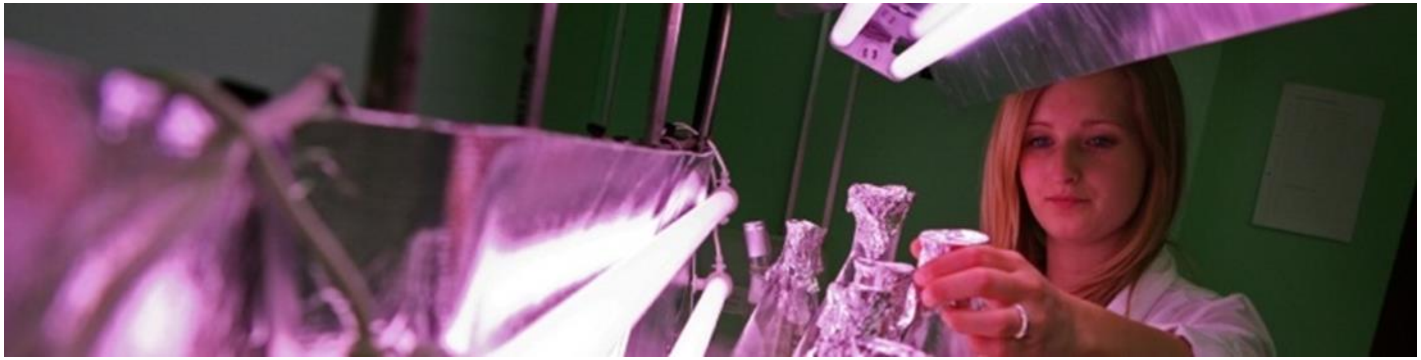

Microalgal-based biorefineries : towards a potential solution for sustainable bioenergy production.

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Avec le soutien de la DGO6
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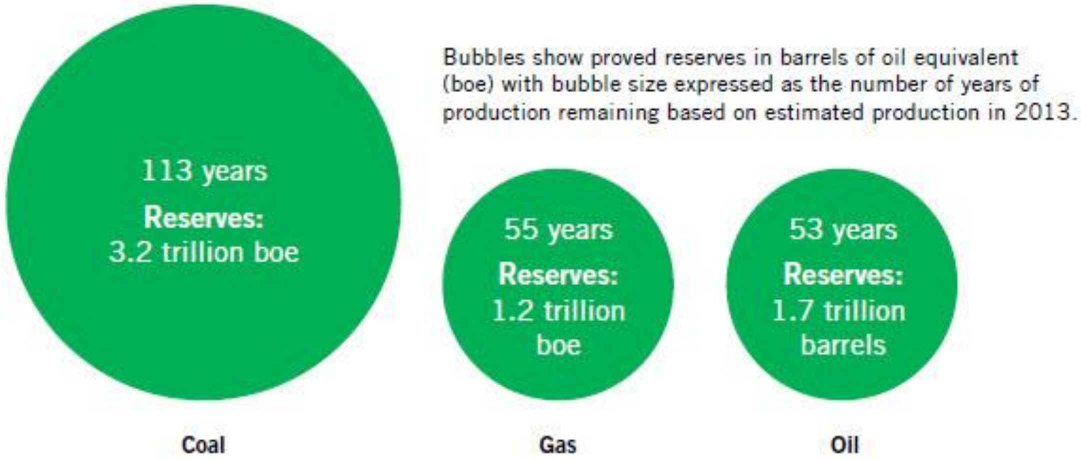
LE FONDS EUROPÉEN DE DÉVELOPPEMENT RÉGIONAL ET LA WALLONIE INVESTISSENT DANS VOTRE AVENIR

Plan

- ✓ Introduction
- ✓ Microalgae as raw materials for biorefinery & circular economy
- ✓ 3G biorefinery
- ✓ Examples of microalgae integration in 3G and environmental biorefineries
- ✓ LCA
- ✓ Improvements
- ✓ Conclusions

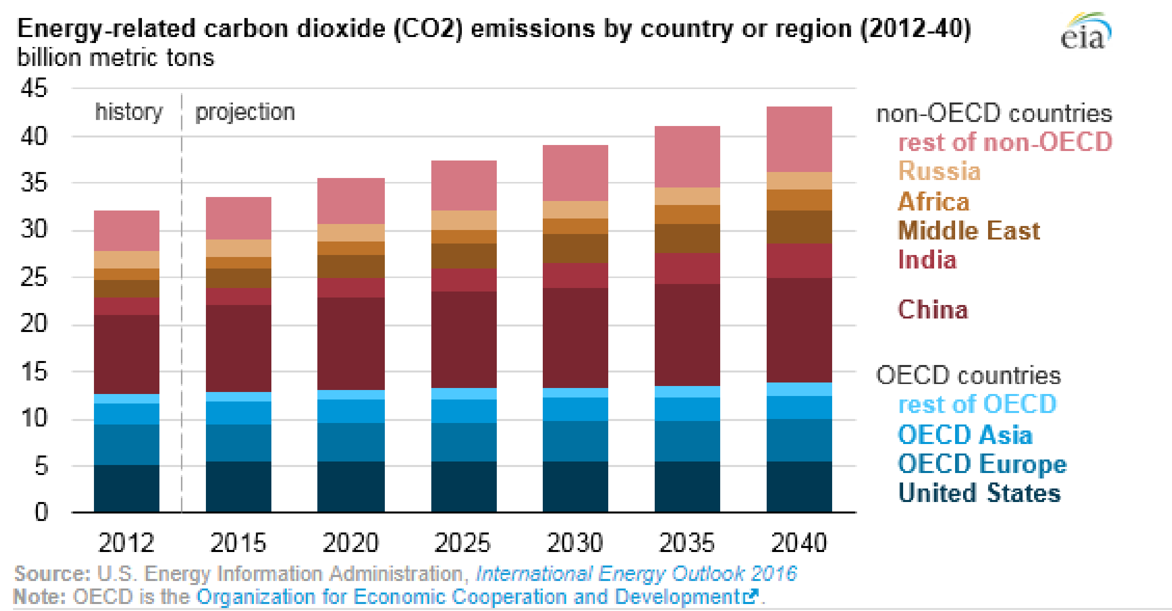
Introduction



Limitation of the fossil ressources

Source: BP, 2014. *Statistical Review of World Energy.* (Note: one trillion = one thousand billion).

Projection of energy-related CO_2 emission



CO_2 Production and Biomitigation

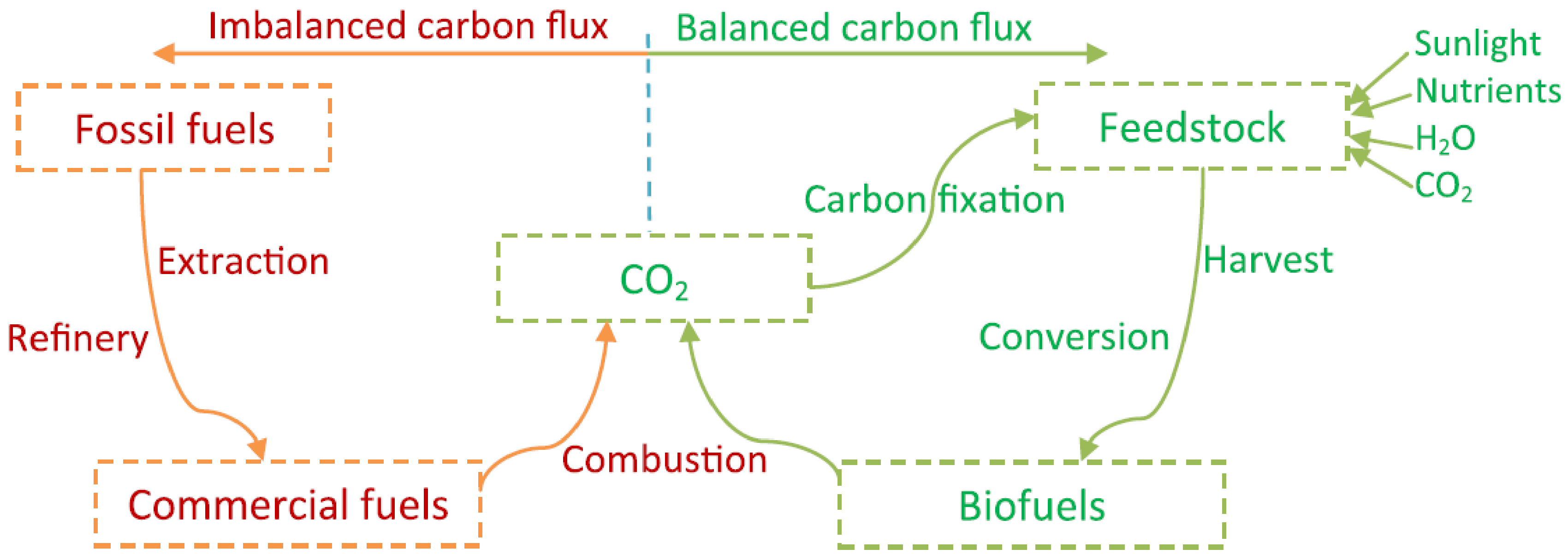
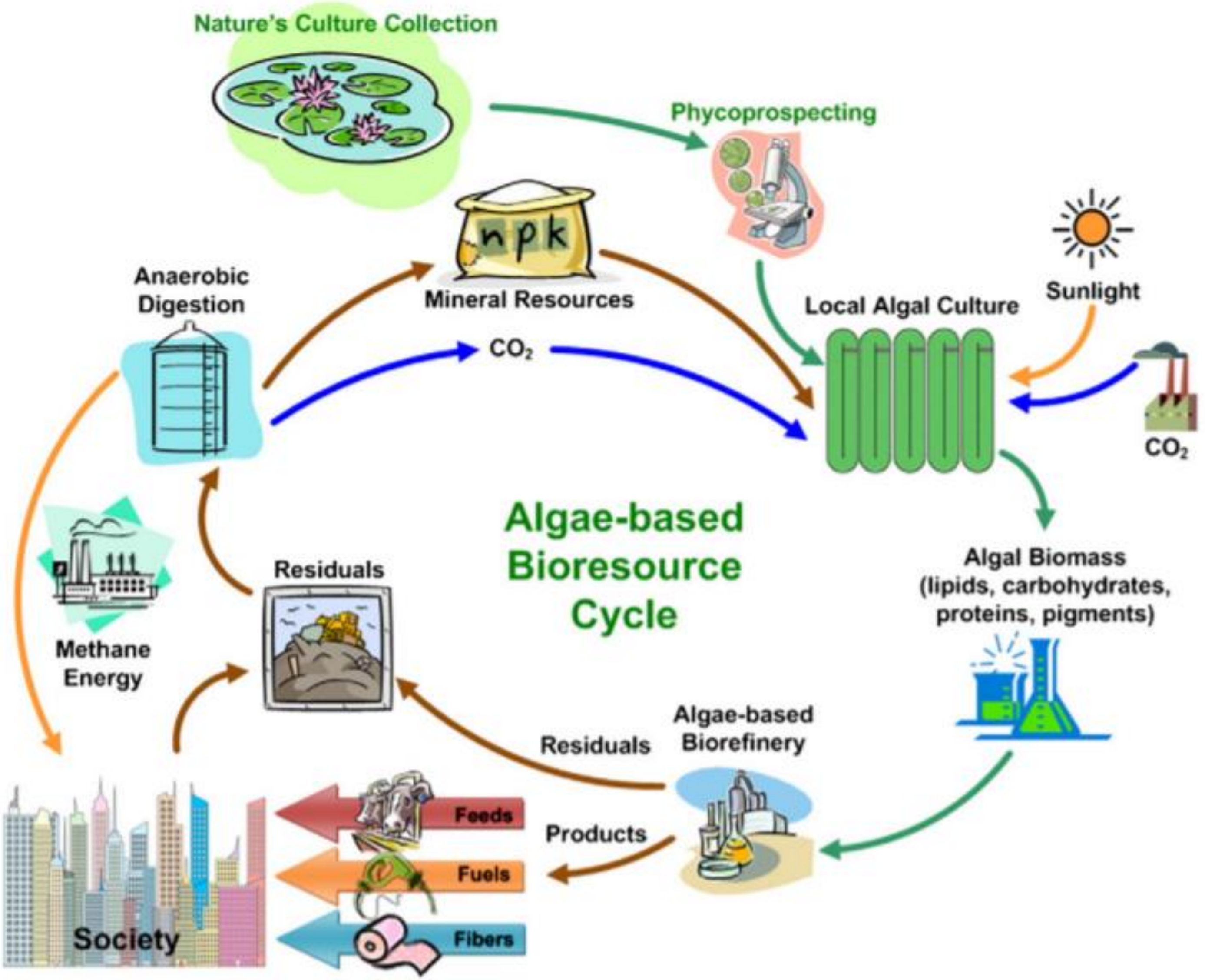
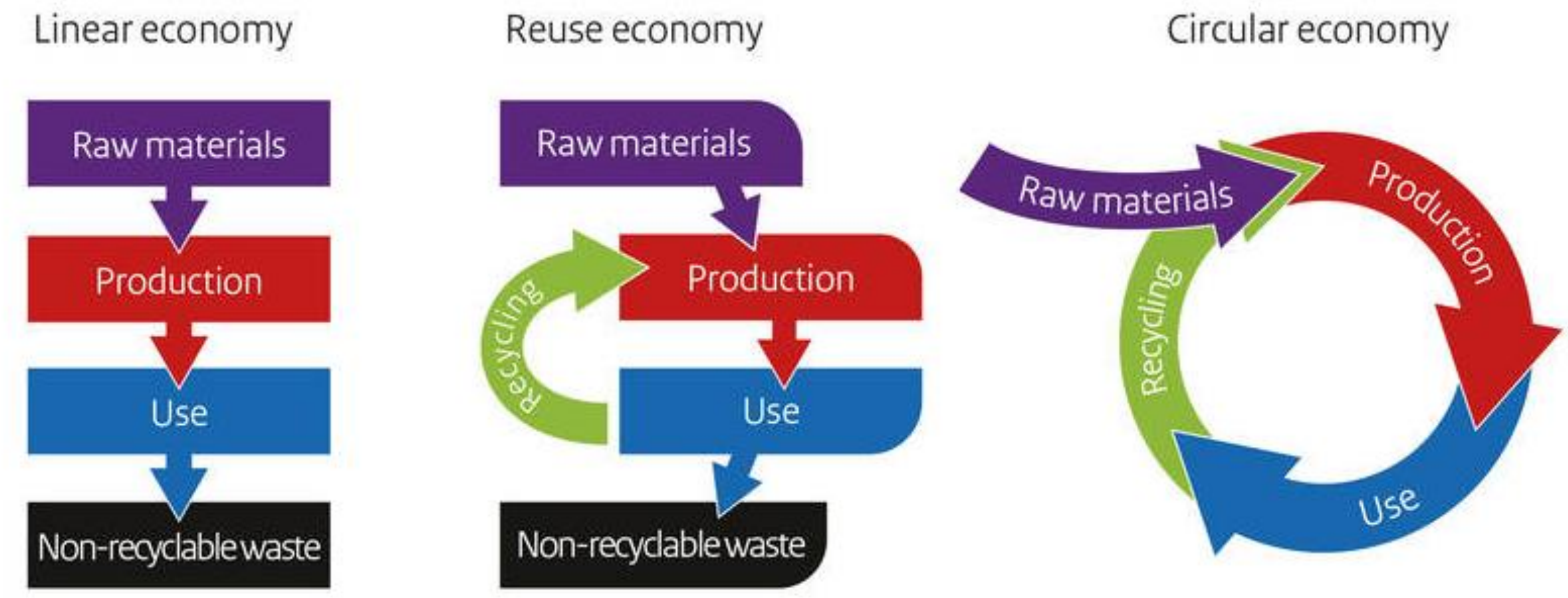


Fig. 2. CO_2 cycle for fossil fuel and biofuels.

Microalgae as raw materials in biorefinery concept and circular economy



Circular economy concept



Past **Present** **Future**

Circular economy

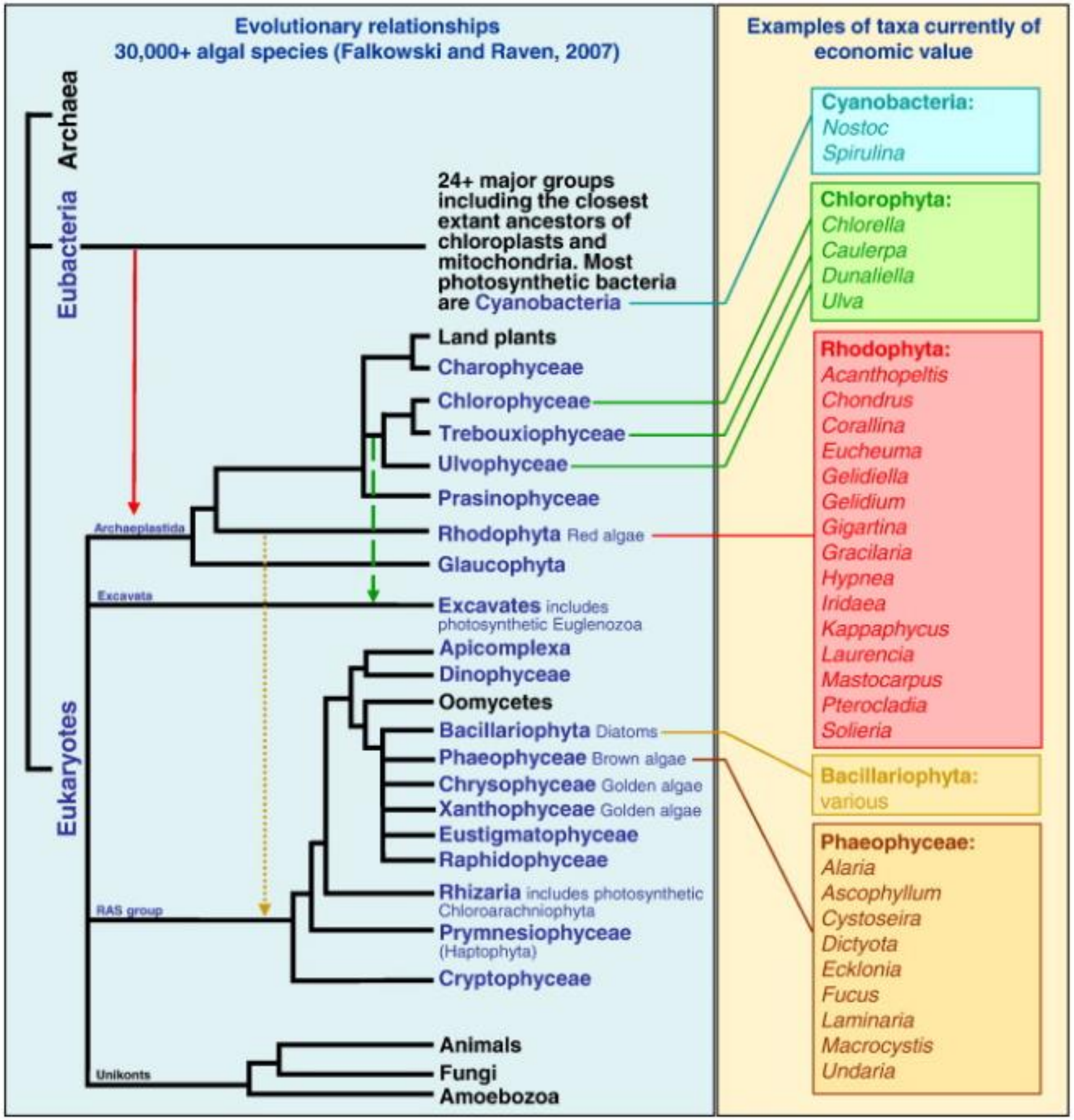
7 Key Principles :

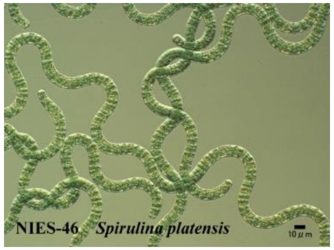
- Ecoconception
- Industrial Ecology
- The functional Economy
- Re-employment
- Repairs
- Ruse
- Recycling

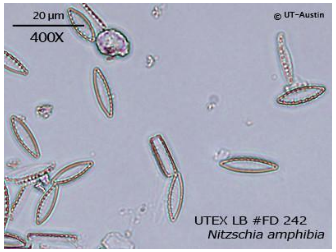
Attempt to reconcile: growth (economic, demographic), resources and environment

Algae : Polyphyletic group of organisms

D.B. Stangel et al. Biotechnology Advances 29 (2011) 483–501

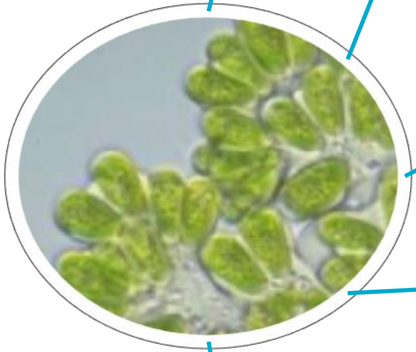






Biochemical composition

High plasticity to direct bioproduction to specific fatty acids or other metabolites of interest



Triacylgy-cerides

Storage lipids
(triacylgycerides with mainly C_{16} to C_{18} fatty acids, unsaturated)
Up to 70% of dry weight

Membrane lipids

Glyco- et phospholipids
(up to 40 % of fatty acids are polyunsaturated, i.e. eicosapentaaenoic acid (EPA))
Up to 7% EPA of dry weight

Carbo-hydrates

Storage products
α-(1-4)-glucane, β-(1-3)-glucane, fructane, glycerol
Up to 50% of dry weight

Proteins

Proteins with all amino acids
Partly soluble and partly bounded as particulate
Up to 50% of dry weight

Valuable compounds

Carotenoids (astaxanthin, fucoxanthin, lutein)
Phytosterols, all vitamins et antioxidants
Antifungal, -viral ou –microbial
From 1 – 5% each of dry weight

Factors Affecting Biochemical Profiles

Factors

- Light (photo-period and intensity)
- Temperature
- Nutrient-status (nitrogen availability)
- Nutrition (media)
- Salinity
- Carbon availability (CO_2 or organic carbon)
- Growth phase

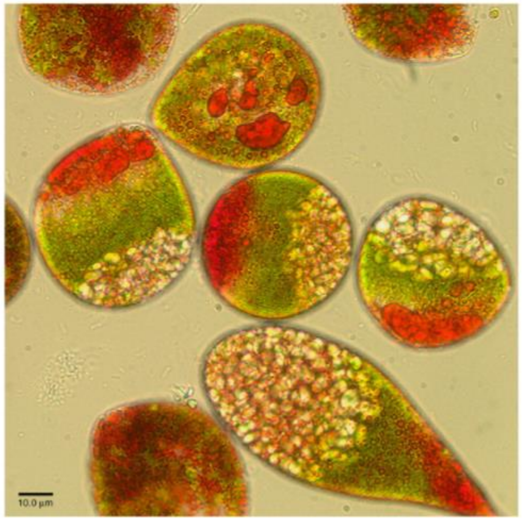
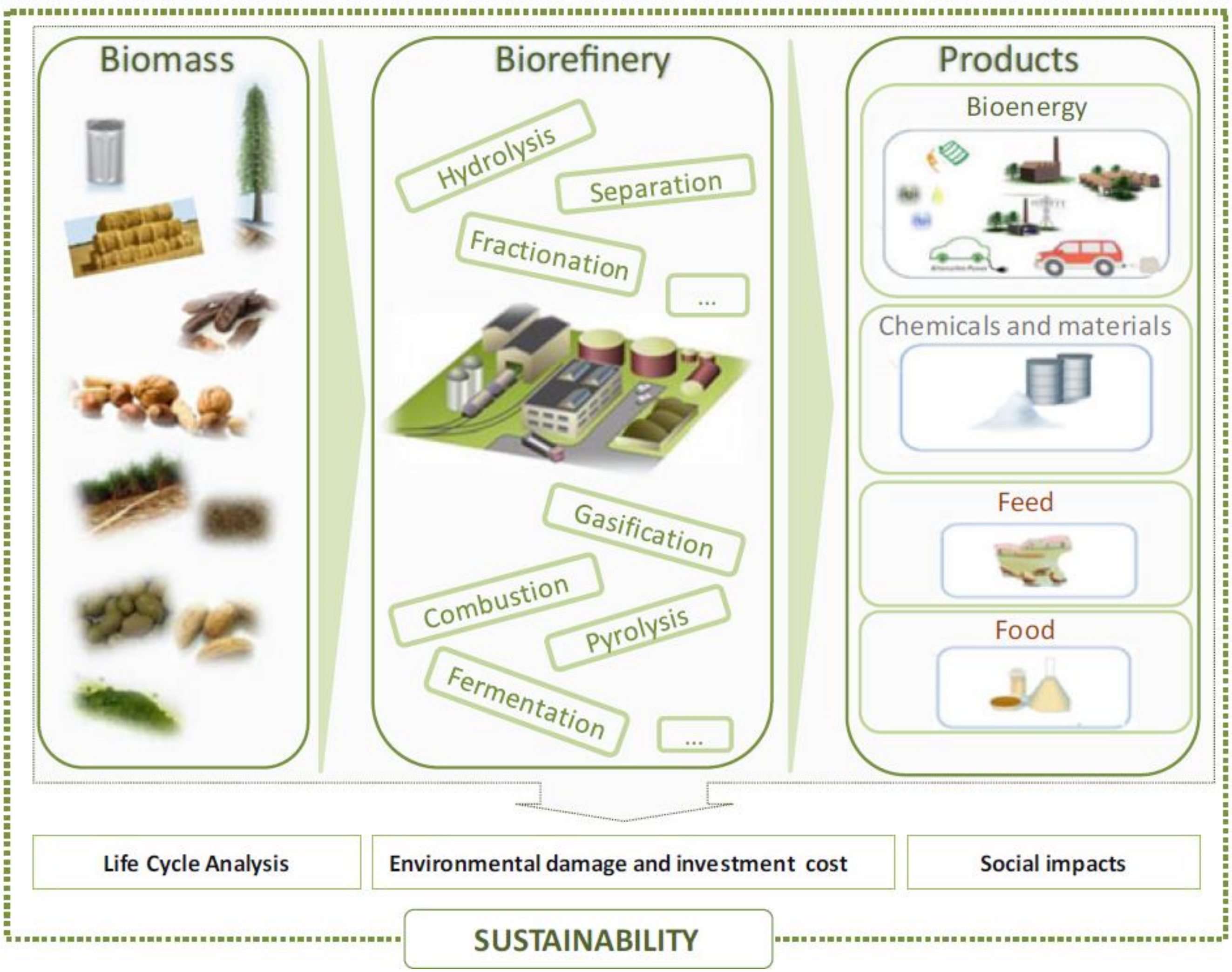


Fig. 3. Indigenous alga with high-value compounds. *Euglena cf. sanguinea* collected from a pond enriched by agricultural run-off. The photo, taken under brightfield transmission illumination, shows distinct regions of red carotenoids (presumably astaxanthin esters), green photosynthetic chlorophyll, and clear paramylon carbohydrate granules (storage material).

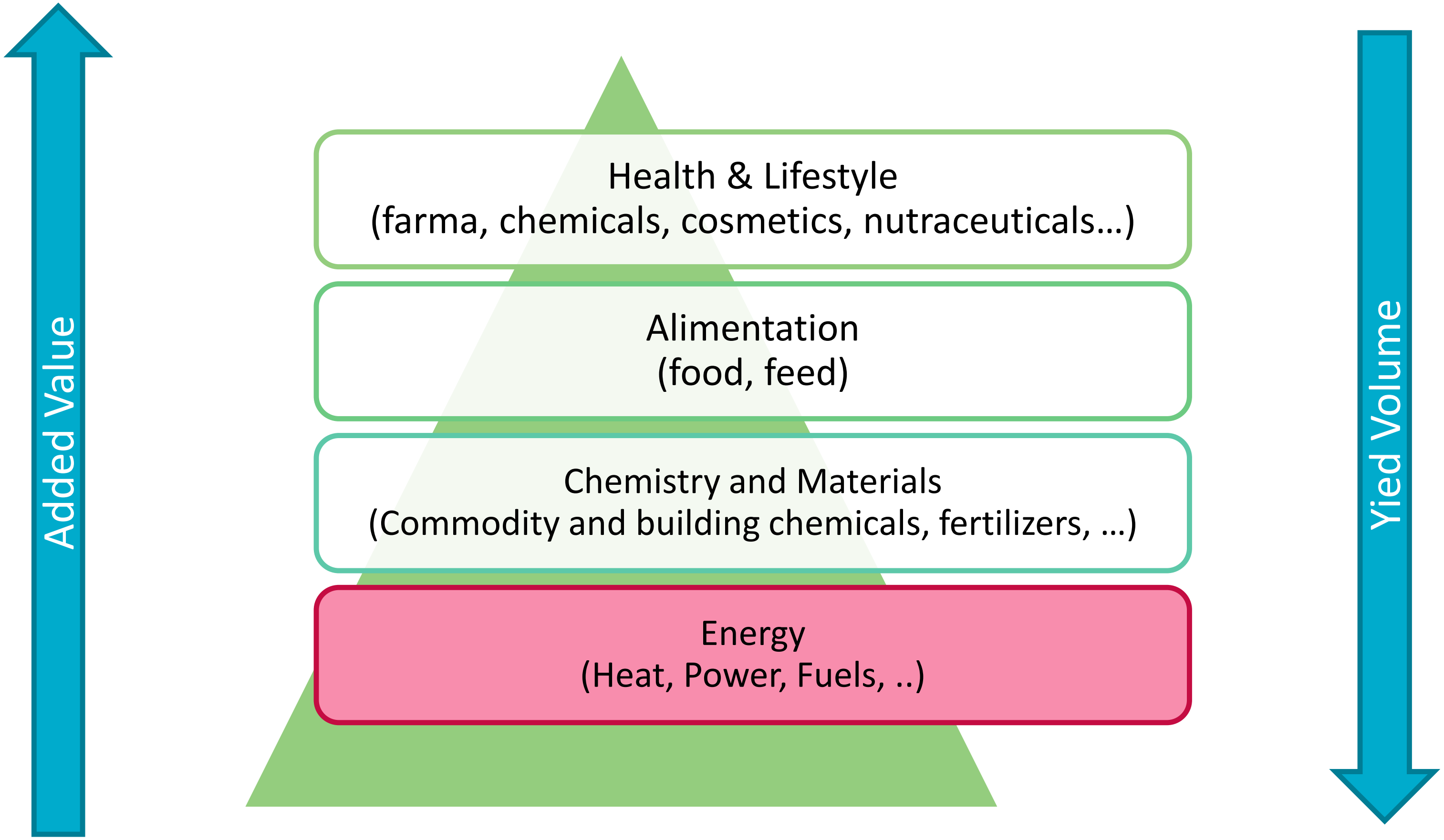
A.C. Wilkie et al. 2011

Affect the biochemical composition and therefore bioproduct potential of microalgae

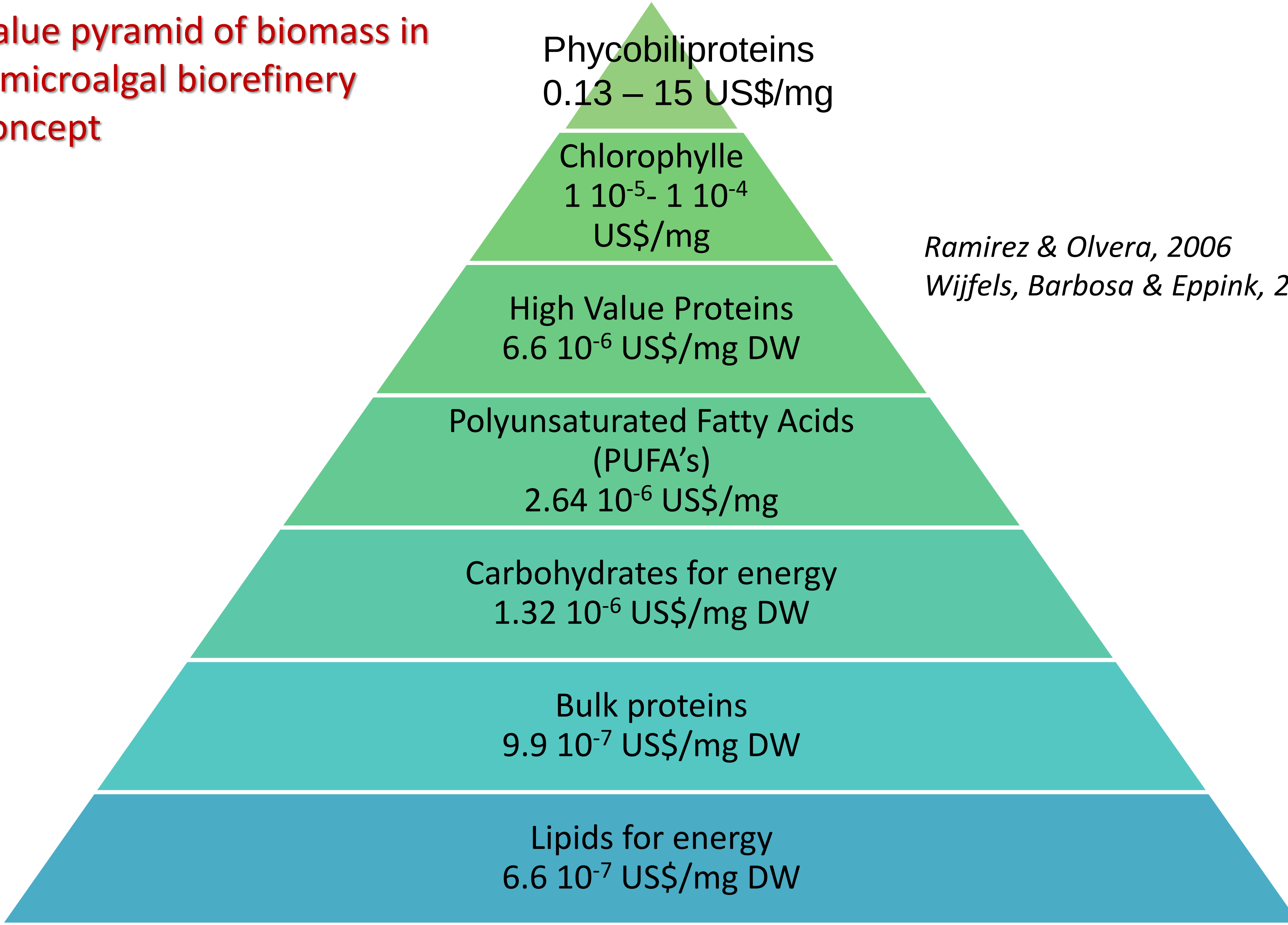
Traditional biorefinery concept



Value pyramid of biomass in a biorefinery concept

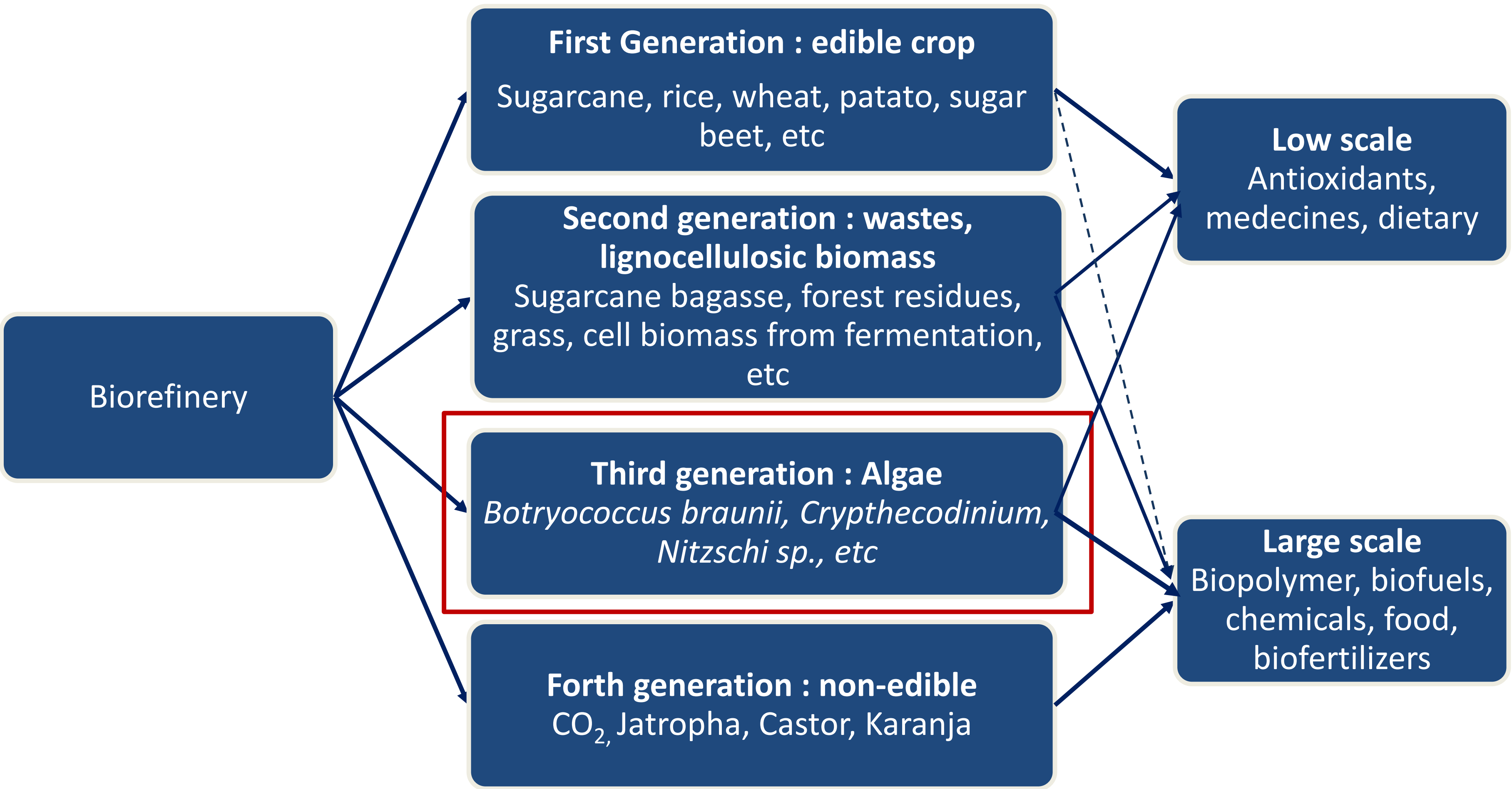


Value pyramid of biomass in a microalgal biorefinery concept



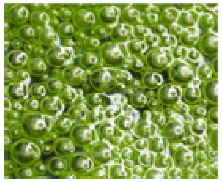
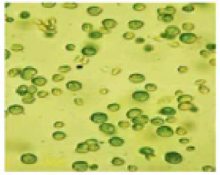
Ramirez & Olvera, 2006
Wijfels, Barbosa & Eppink, 2010

Microalgae : 3G biorefinery



Adapted from Romeo-Garcia et al. 2017

Comparaison between the 3 generations of biofuels based on their feedstaookc 1G to 3G

Generations of Biomass Feedstock	Prosperities
1st Generation (food crops)	
Starchy Materials: Corn  Sucrose-Containing Feedstocks: Sugar Beet  Sugar Cane 	1. Produced mainly from agricultural crops traditionally grown for food and animal purposes 2. Causes food crisis and contributes to higher food prices, carbon stores, and land use
2nd Generation (waste and energy crops)	
Lignocellulosic biomass: Wood residues  Straw  Energy Crops 	1. Produced from non-edible crops grown on non-arable land 2. Produced from wood waste, agricultural waste, energy crops, organic waste, waste water, and landfill wastes 3. Harder to extract the required fuel
3rd Generation	
Algae   	1. Most microalgae grow through photosynthesis by converting sunlight, CO2, and a few nutrients, including nitrogen and phosphorous, into biomass 2. Algae can be grown using non-arable land and water unsuitable for food production (brackish, sea and wastewater), therefore reducing the strain on already depleted water sources 3. High yield per acre 4. Minimal impact on fresh water resources 5. Using CO_2 emissions from power plants 6. The oil productivity of microalgae is greater than that of other energy crops

G.M. Elrayies - Renewable and Sustainable Energy Reviews 81 (2018) 1175–1191

Microalgae : 3G biorefinery

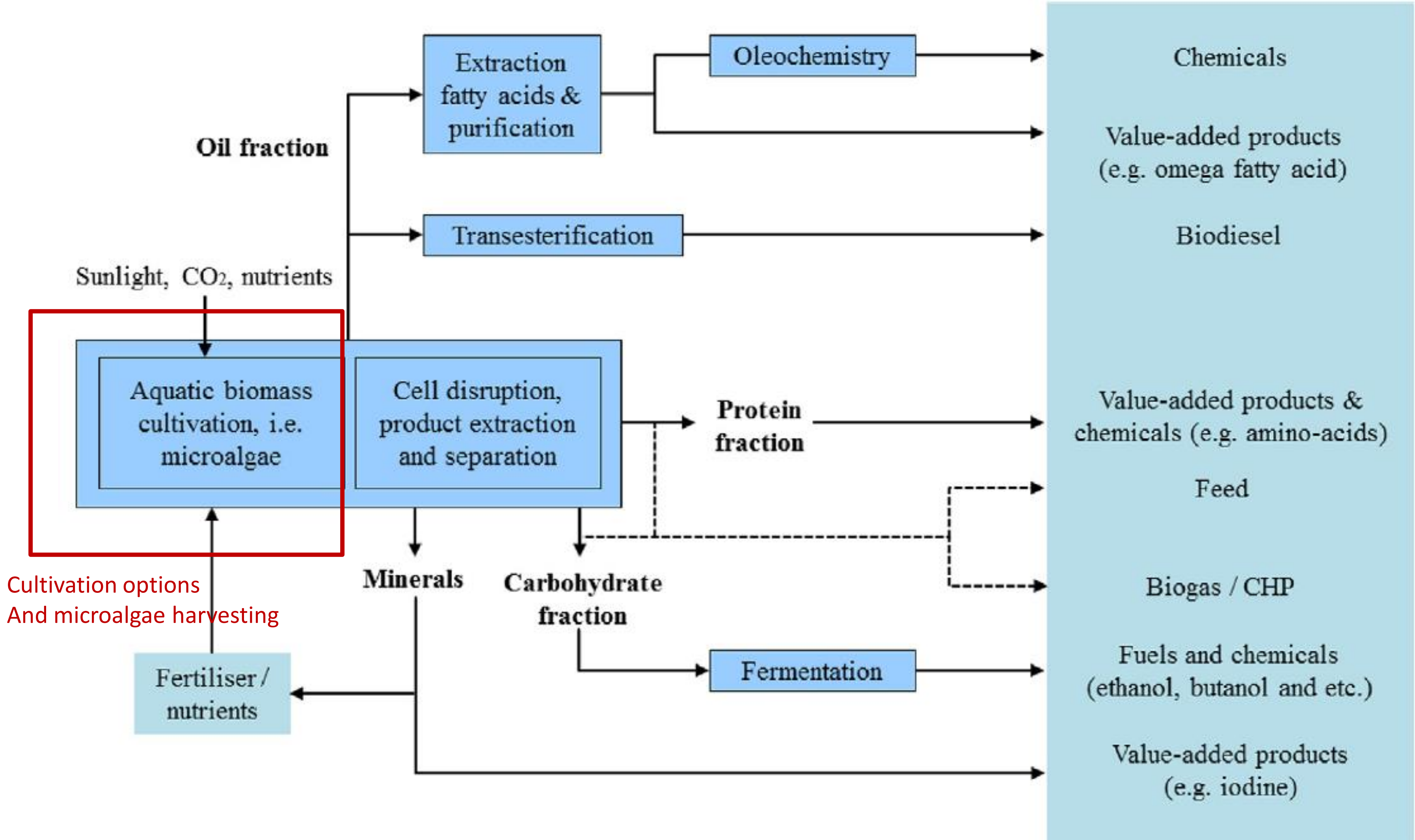
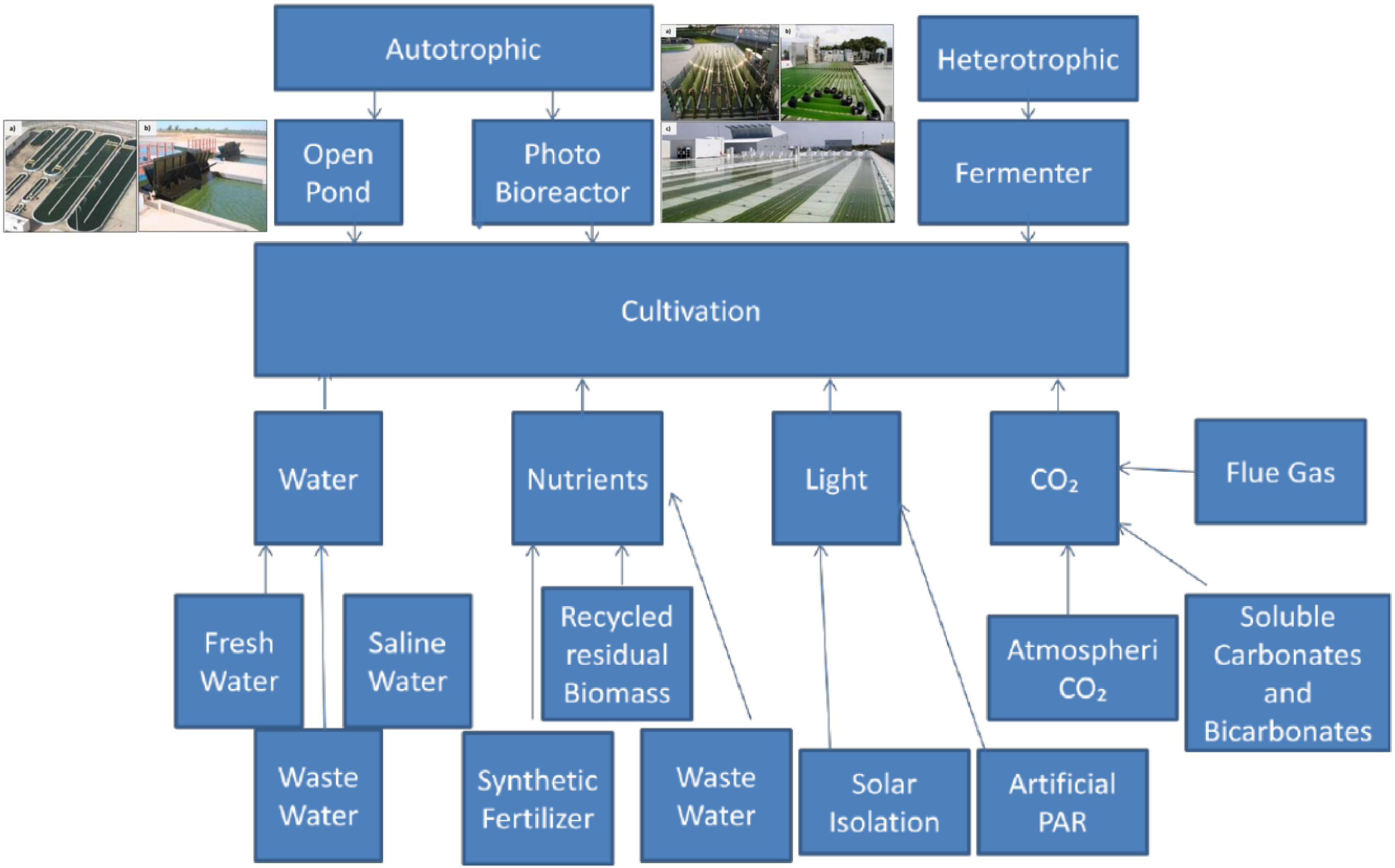


Fig. 1. Applications in microalgae biorefinery.

Algal Cultivation Options



Microalgae harvesting

Screening

Thickening :

- Coagulation/ Floculation/ Biofloculation
- Electrical methods

Separation :

- Gravity separation
- Dissolved air flottation (DAF)

Dewatering :

- Filtration
- Centrifugation

Drying

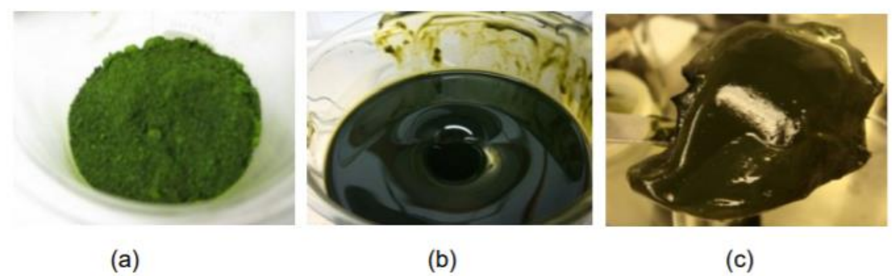


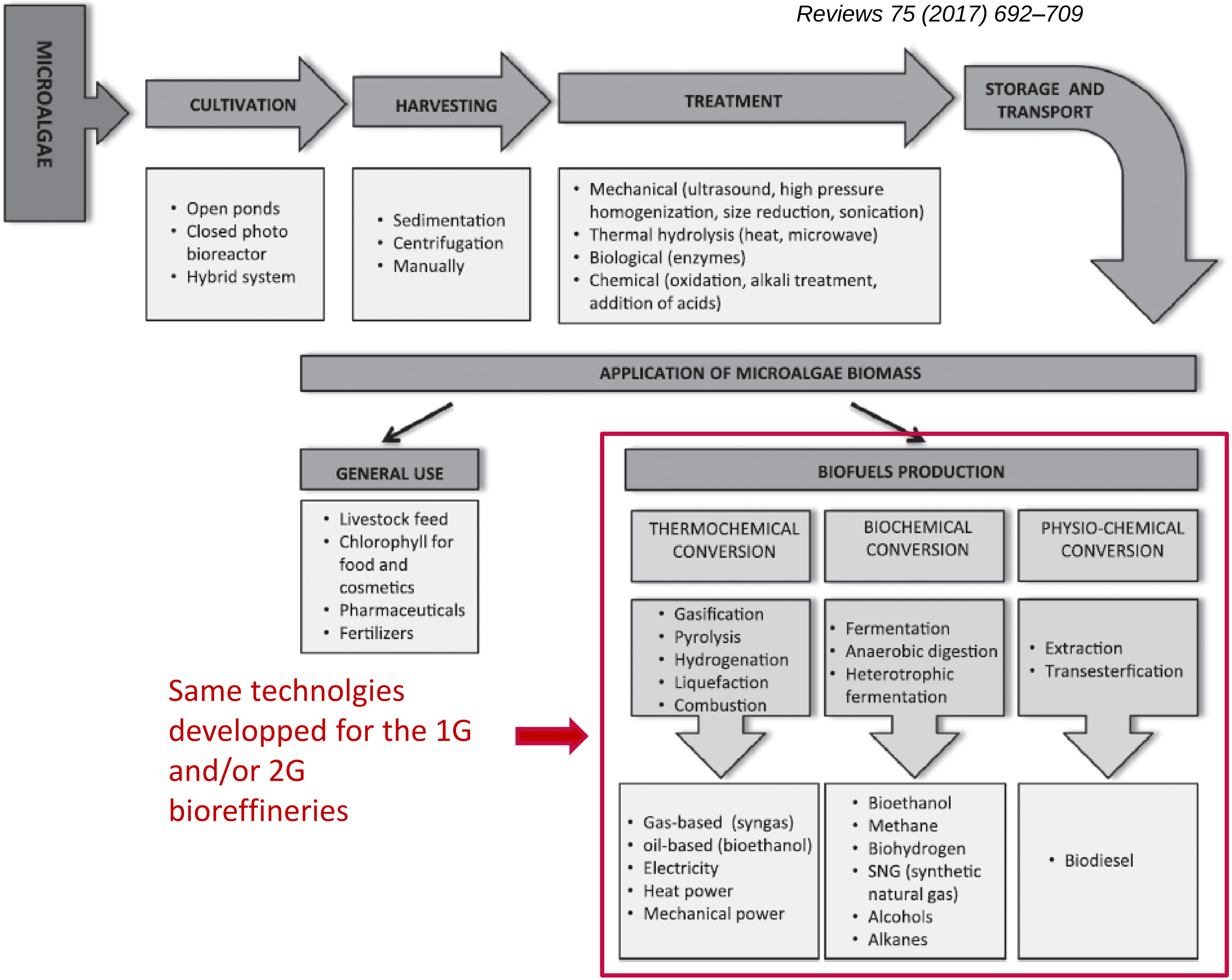
Figure 14. Algae as dried product (a) and suspension (b), and the centrifuged algal biomass (c).

Comparison of algal harvesting methods (Udumann et al. 2010).
TSS = total suspended solids.

Dewatering process	Highest possible yield	Energy usage
Centrifugation	>22% TSS	Very high - 8 kWh/m^3
Flocculation	>95% removal of algae	Low for slow mixing: varies largely
Natural filtration	1-6% TSS	Low (vibrating screen) - 0.4 kWh/m^3
Pressure filtration	5-27% TSS	Moderate (chamber filter press) - 0.88 kWh/m^3
Tangential flow filtration	70-89% removal of algae	High - 2.06 kWh/m^3
Gravity sedimentation	0.5-1.5% TSS	Low (lamella separator) - 0.1 kWh/m^3
Dissolved air flotation	1-6% TSS	High - 10-20 kWh/m^3
Dispersed air flotation	90% removal of algae	High
Electrocoagulation	99.5% TSS	Medium to high - 0.8-1.5 kWh/m^3
Electroflotation	3-5% TSS	Very high
Electrolytic flocculation	>90% removal of algae	Low to medium - 0.33 kWh/m^3

High energy consumption

E. Jankowska et al. Renewable and Sustainable Energy Reviews 75 (2017) 692–709



Same technolgies developped for the 1G and/or 2G bioreffineries

Fig. 1. Microalgae process value chain.

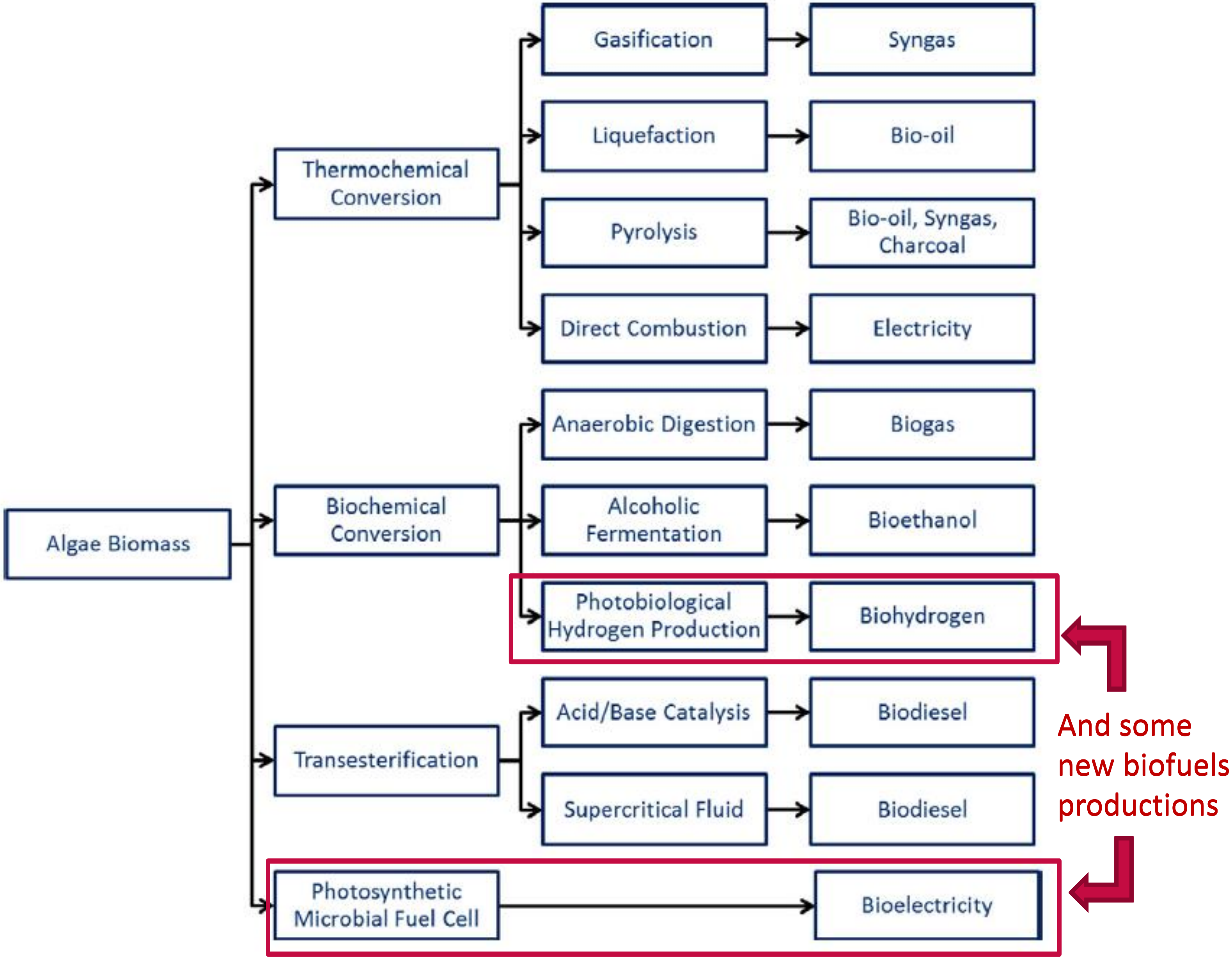
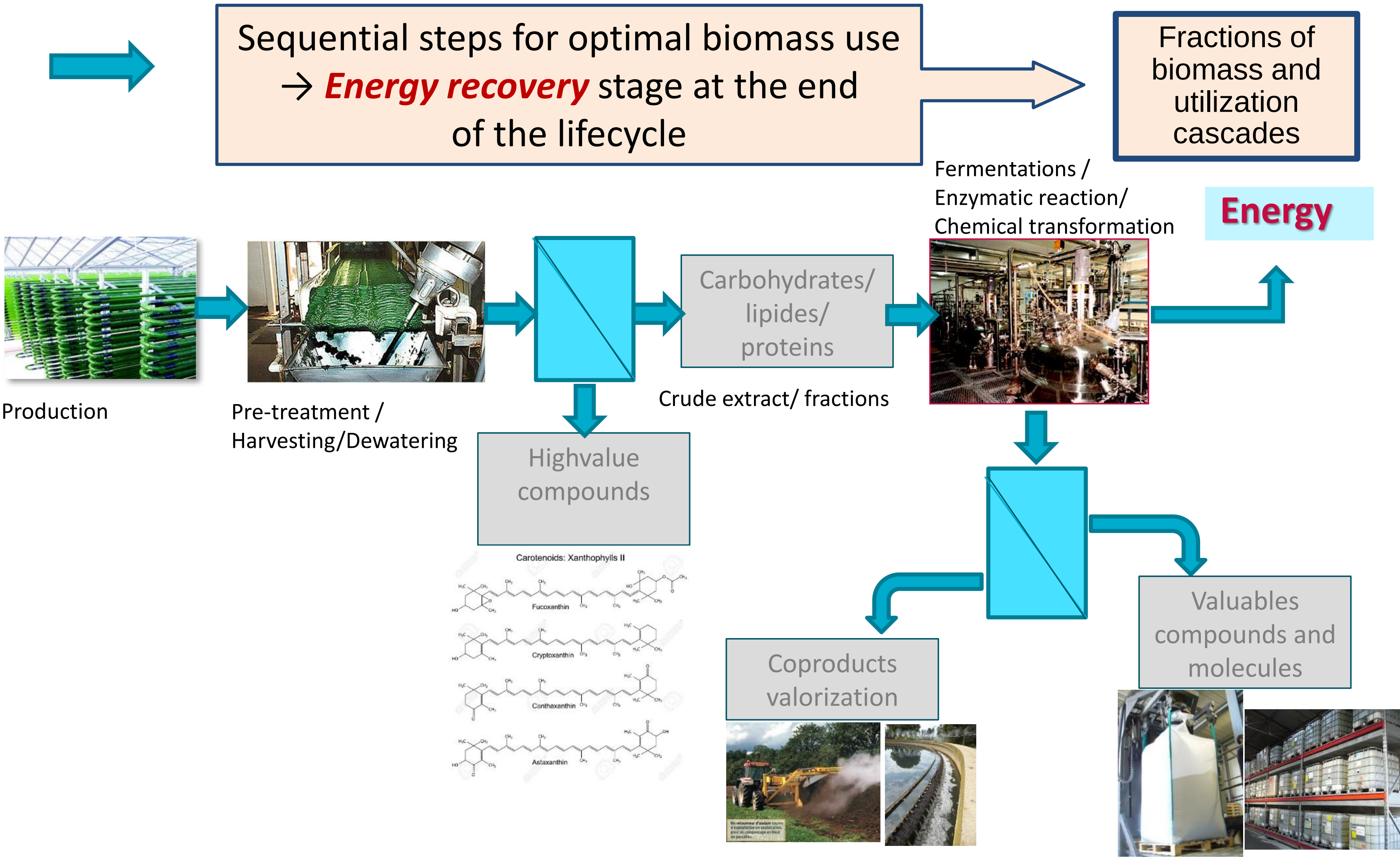


Fig. 2. Algal biomass conversion processes for biofuels production.

Mainstream Biorefinery with Microalgal Biomass Cascad Principle



Microalgae for waste treatment and valorization : Environmental Biorefineries

Problem ⟷ Process ⟷ Products

Problem

Waste gases

Waste water

Process

Benefitting Industries

Coal-fired Power Stations
Underground coal mines

Metal refineries

Waste water remediation

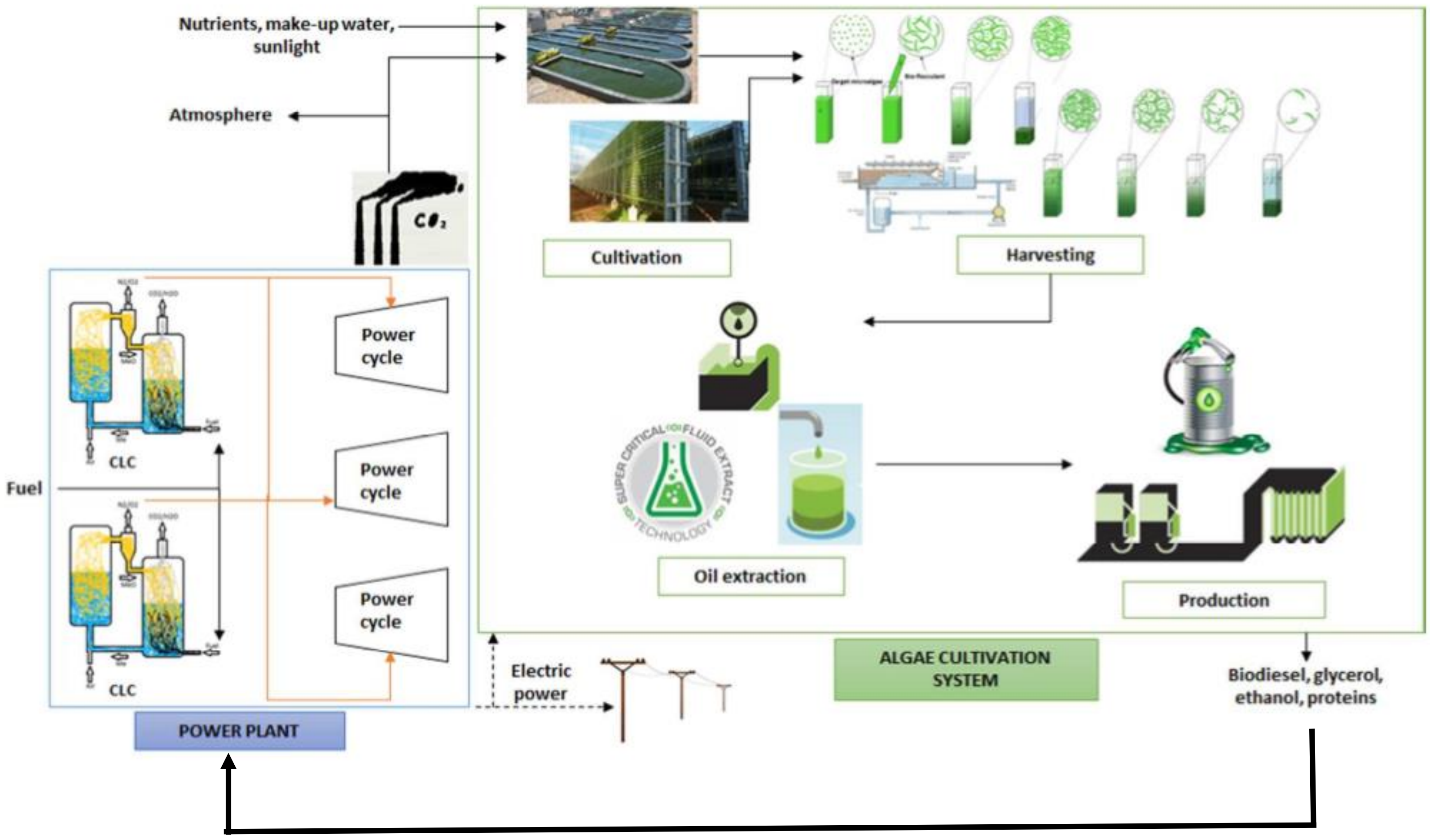
Algae Cultivation

Outcomes
GHG emission abatement
Water recycling
Nutrient remediation
Bioremediation (metals)

Products

- Animal feeds
- Algal biofuels
- Fertilizer/Biochar
- Biorefining
- Nutraceuticals → Carotenoids

CO_2 biomitigation in a power plant using chemical looping combustion and microalgae cultivation for biofuel production



Mungui-Lopez et al. 2018

Nutriment rich Wastewater as feedstock

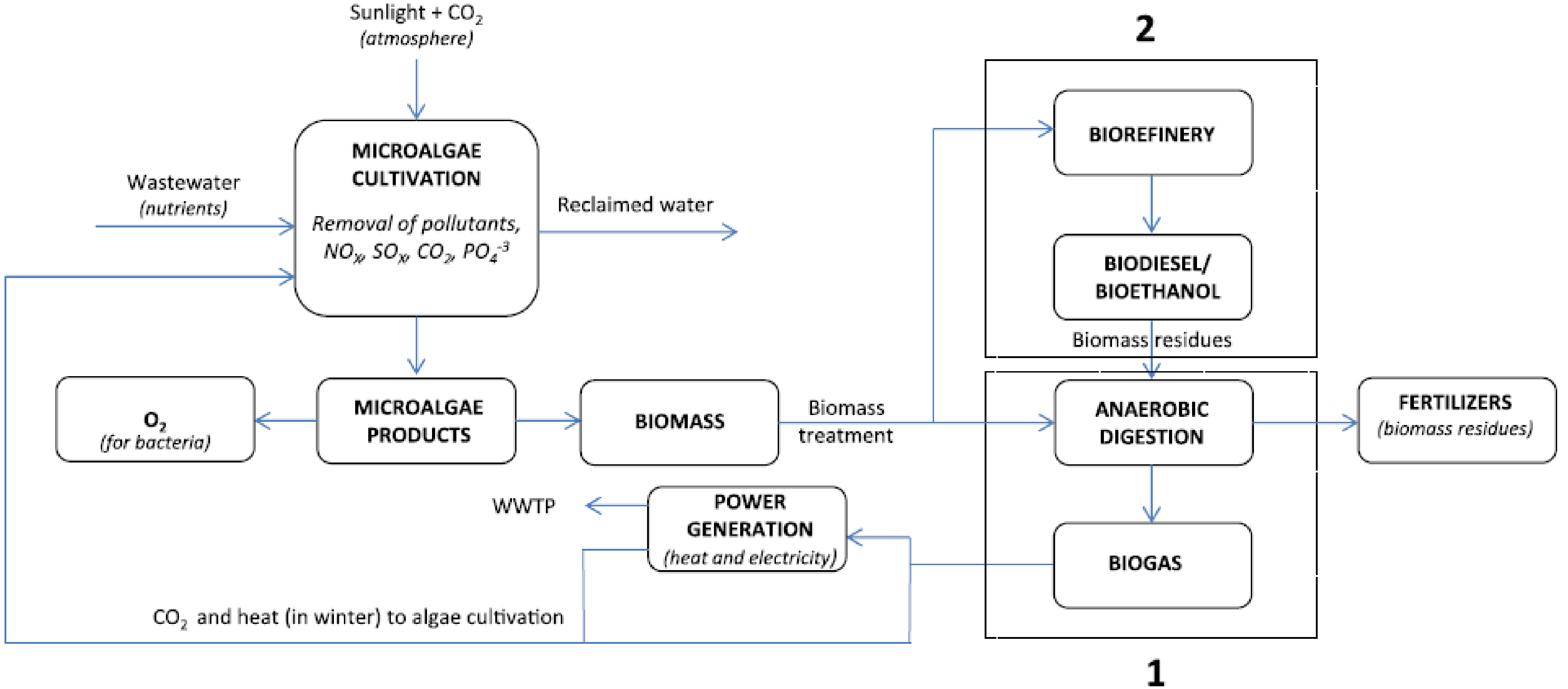


Fig. 2. Possible use of microalgae at the Wastewater Treatment Plant – 1. Anaerobic digestion, 2. Biorefinery.

E. Jankowska et al. Renewable and Sustainable Energy Reviews 75 (2017) 692–709

Table 5
Biomass and lipid productivities and nutrient removal from wastewaters for different microalgae species.

Substrate	Specie	N (mg/L)	P (mg/L)	Biomass (mg/L·d)	Lipid (mg/L·d)	Nutrient Removal	Reference
Raw wastewater	*Desmodesmus sp.* mixed with cyanobacteria	42.13	35.4	13	1.7	84% N 61% P removal	[89]
Treated wastewater	*Scenedesmus sp.*	28.85	3.51	267	15.19	90% N & P removal	[90]
Municipal centrate	*Hindakia sp.*	134	212	275	77.8	–	[91]
Municipal centrate (50%)	*Muriellopsis sp.*	150	18	113	–	90% N & P removal	[92]
Municipal centrate (50%)	*Nannochloropsis gaditana*	338	25	400	–	90% P removal	[93]
Landfill leachate (10%) and municipal wastewater	Microalgae-bacteria consortium	221.6	3.19	131.7	24.1	95% ammonia-N removal	[94]

L. Moreno-Garcia et al. Renewable and Sustainable Energy Reviews 76 (2017) 493–506

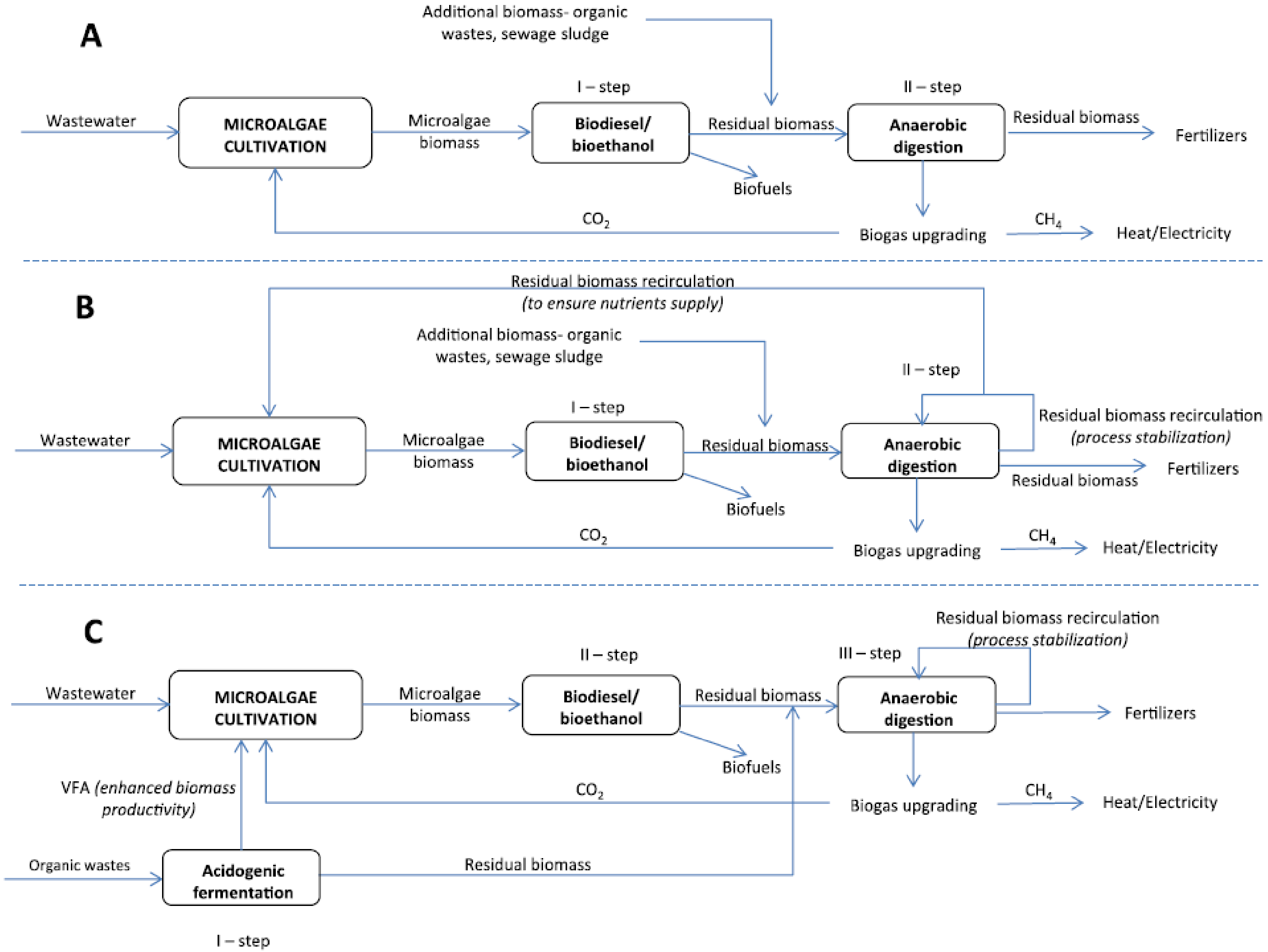


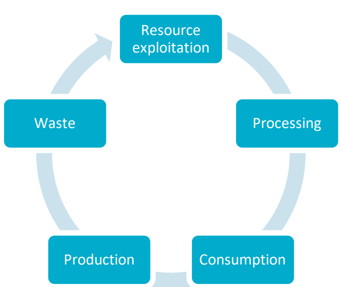
Fig. 3. Microalgae biorefinery concepts: A – two-step biorefinery for biodiesel, bioethanol and biogas production, B – two-step biorefinery with recirculation for enhanced process stability, C – three-step biorefinery with acidogenic fermentation for enhanced microalgae production.

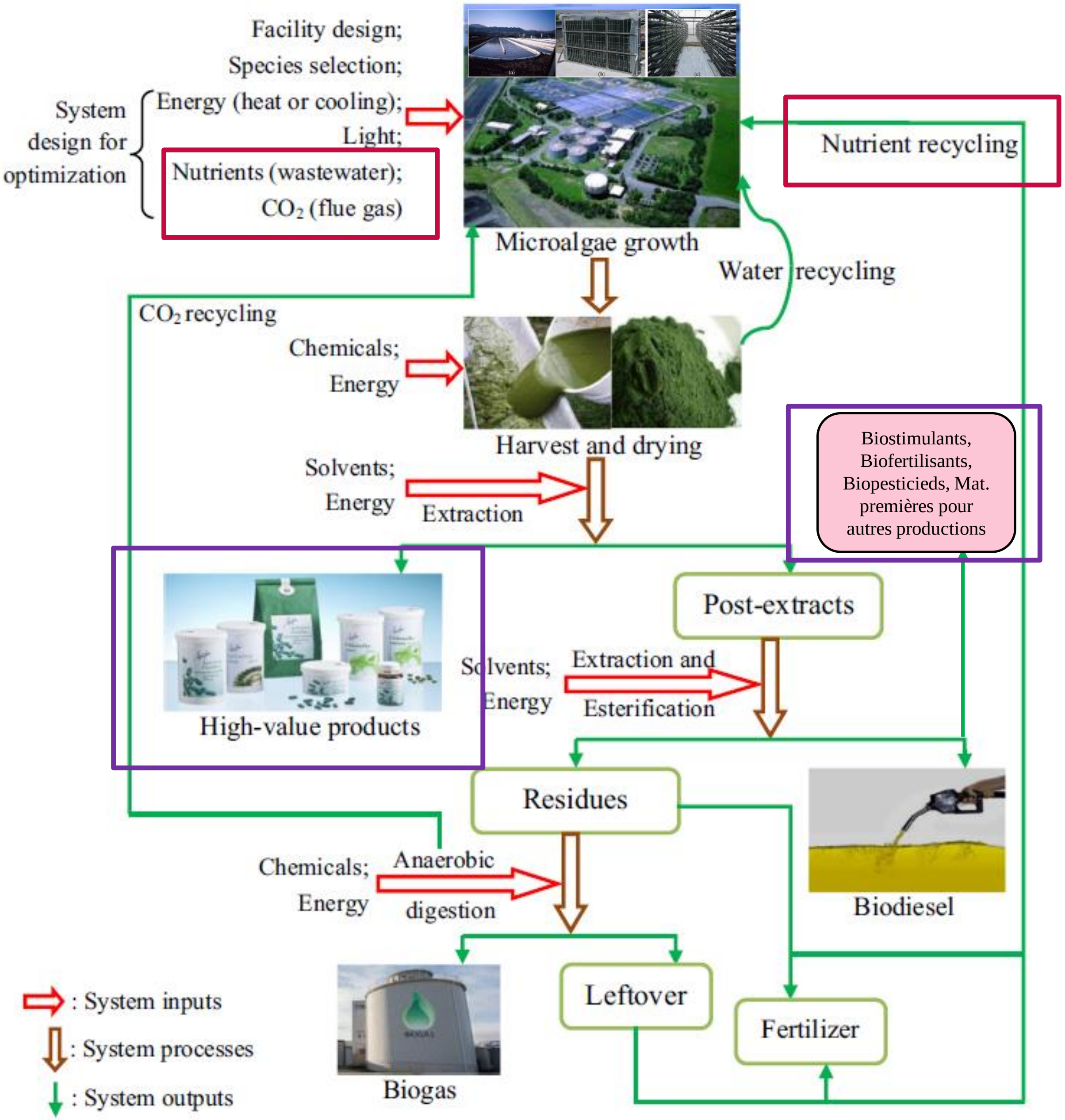
E. Jankowska et al. Renewable and Sustainable Energy Reviews 75 (2017) 692–709

Microalgal biorefinery integrating recovery and recycling of gaseous and liquid industrial effluents + by-products

Integrated environmental biorefinery

Circular economy concept

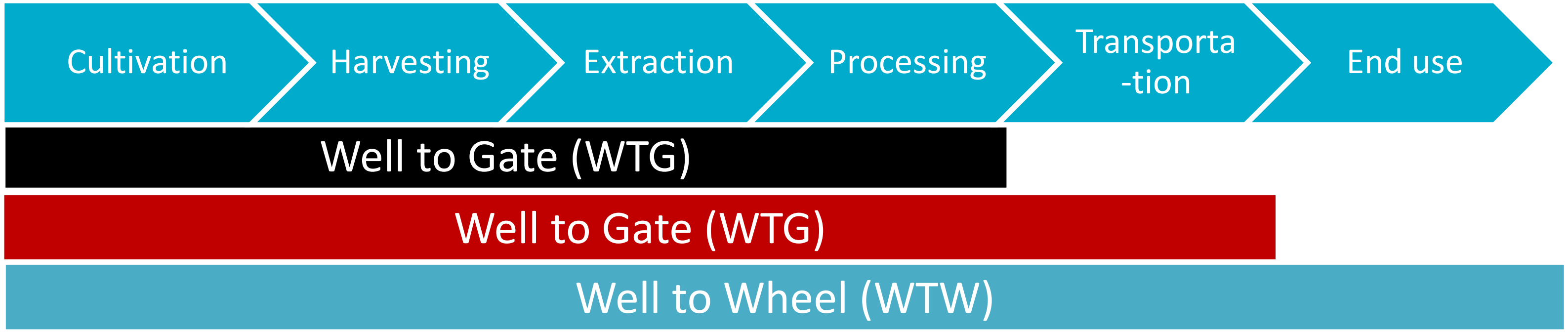


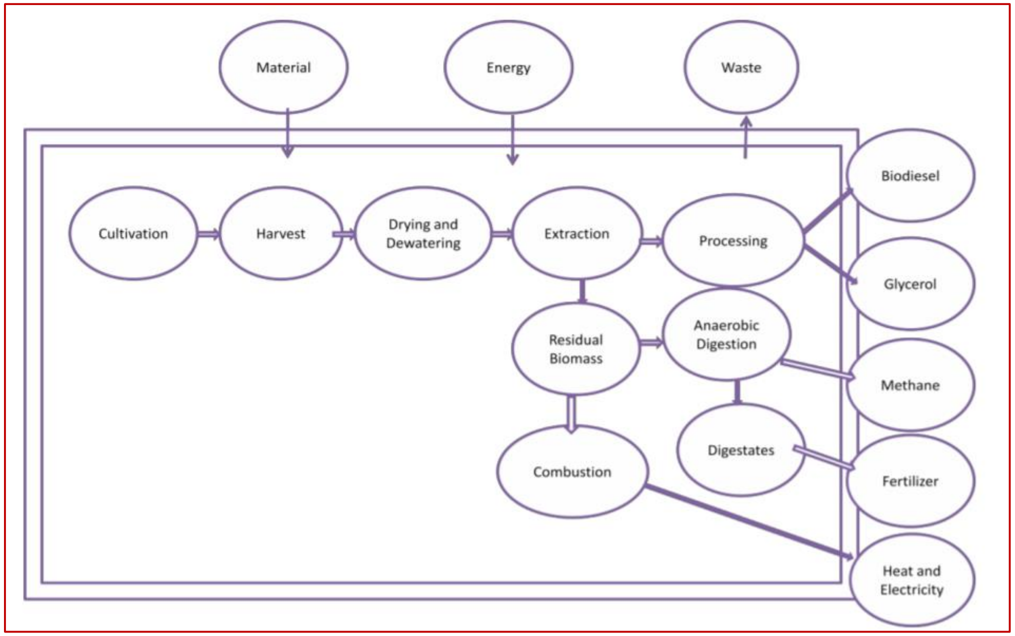


Adapted from Zhu 2015

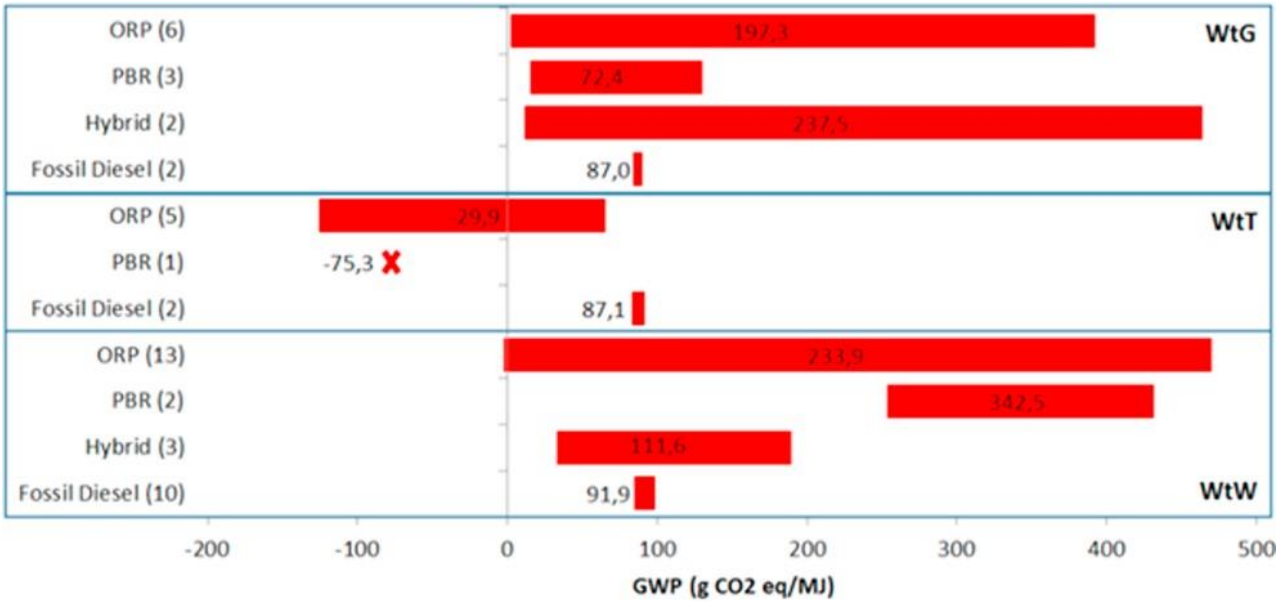
Life cycle assessment

Different LCA approaches for algal biofuels





Exemple of biofuel production pathway and residual processing options for LCA



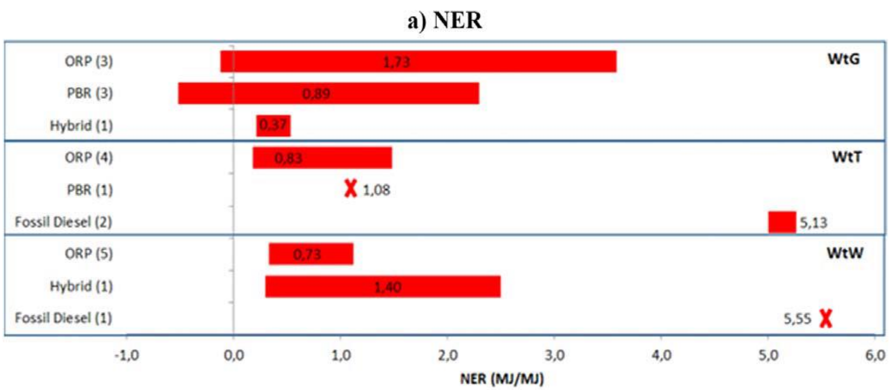
LCA for microalgal biodiesel production for different scenarios

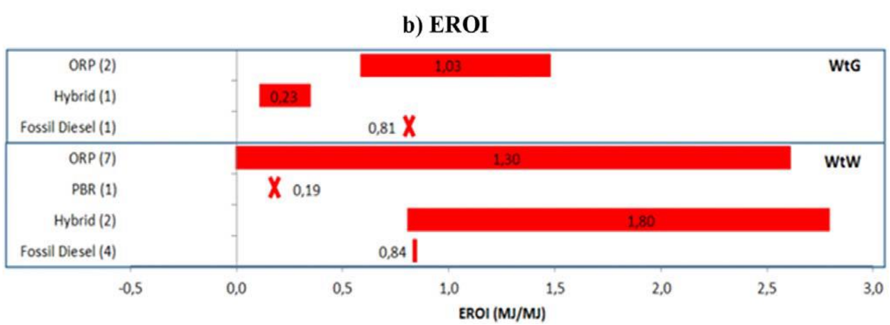
NER and EROI of microalgae biodiesel

$$NER = \frac{Total\ energy\ output}{Total\ energy\ input}$$

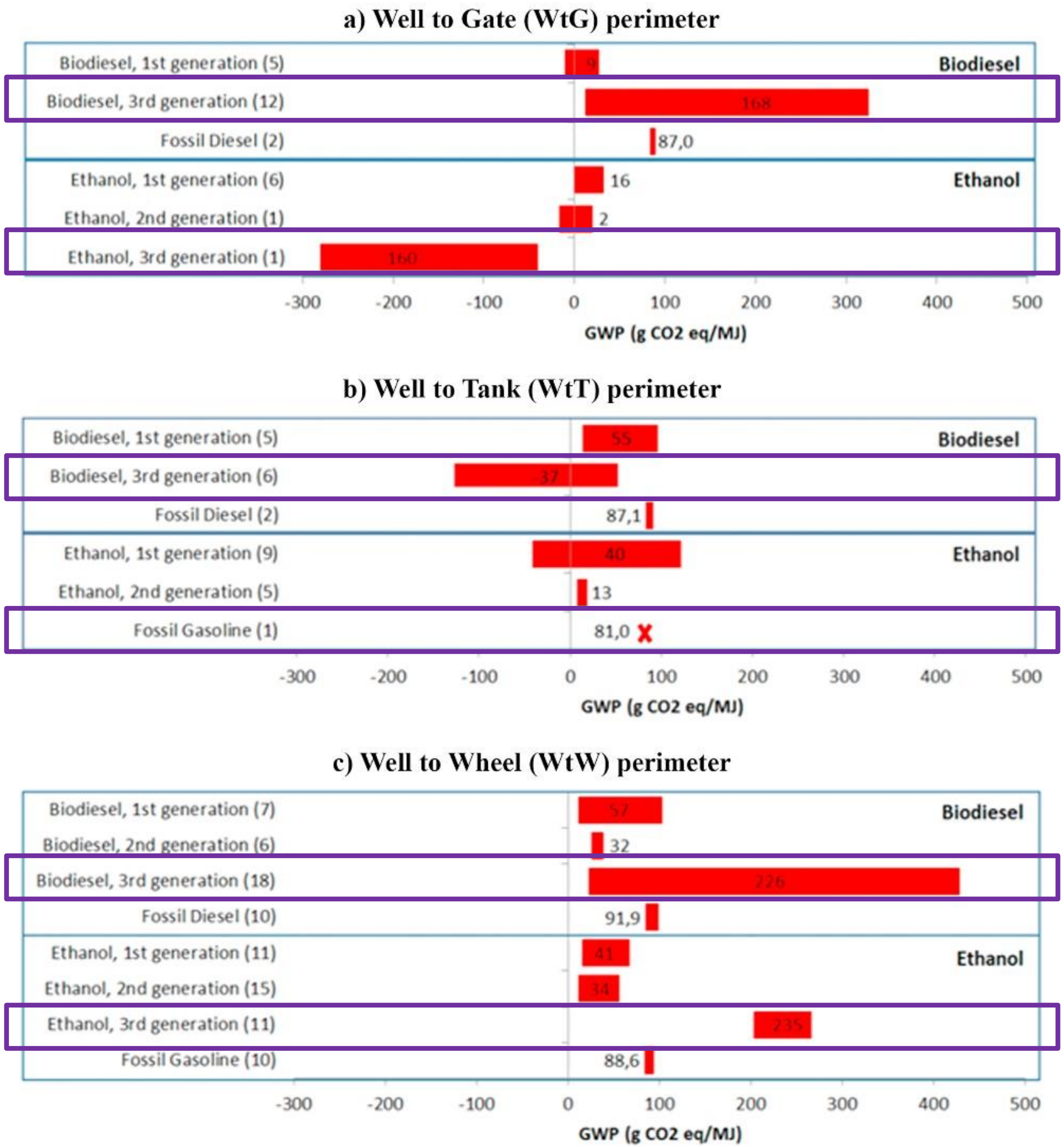
$$EROI = \frac{Total\ energy\ output}{Total\ fossil\ energy\ input}$$

With « total energy output » = biofuel only or (biofuel + co-products)





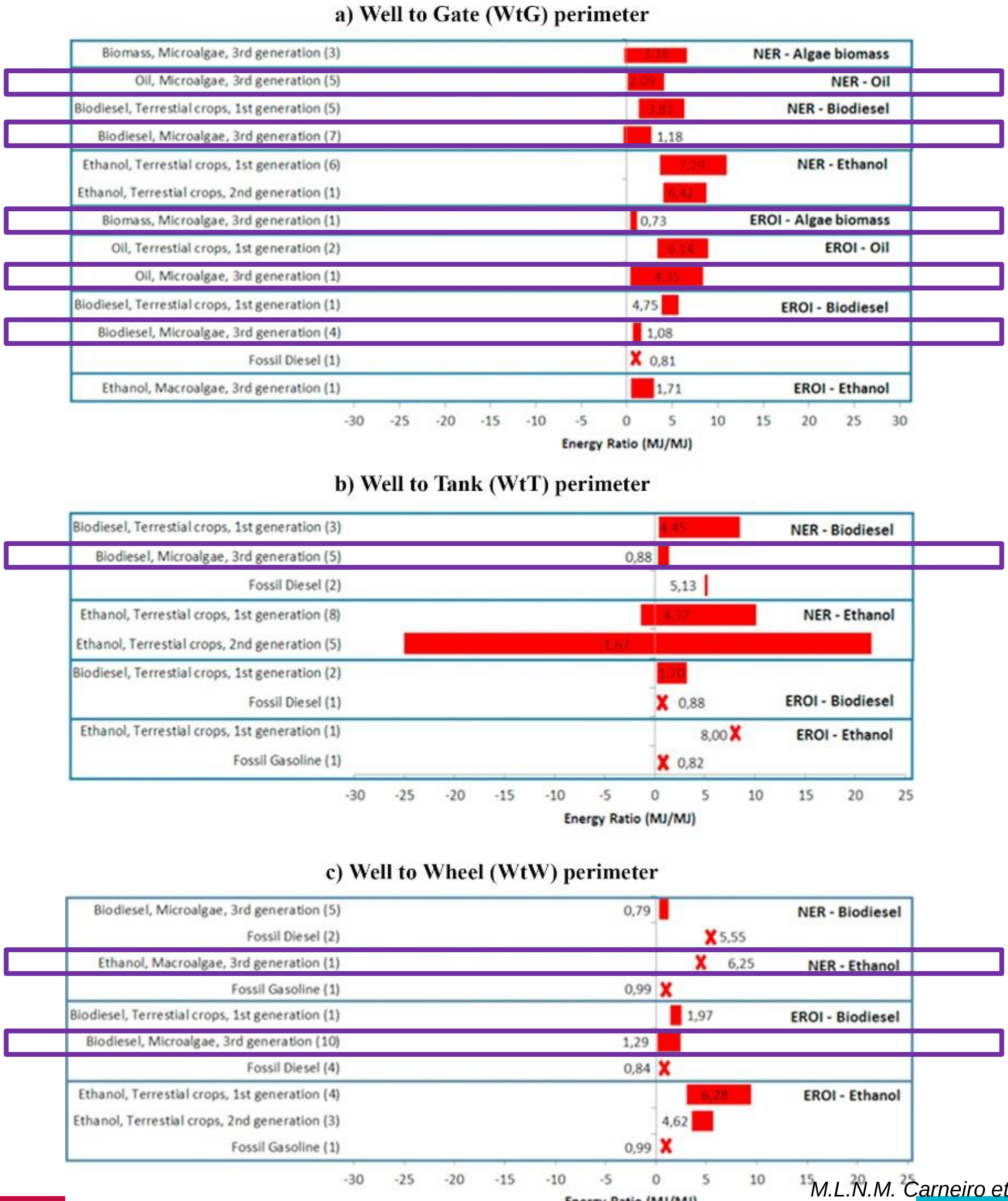
M.L.N.M. Carneiro et al. Renewable and Sustainable Energy Reviews 73 (2017) 632–653



LCA comparaison for the 3 biofuel generations in terms of CO_2 emissions

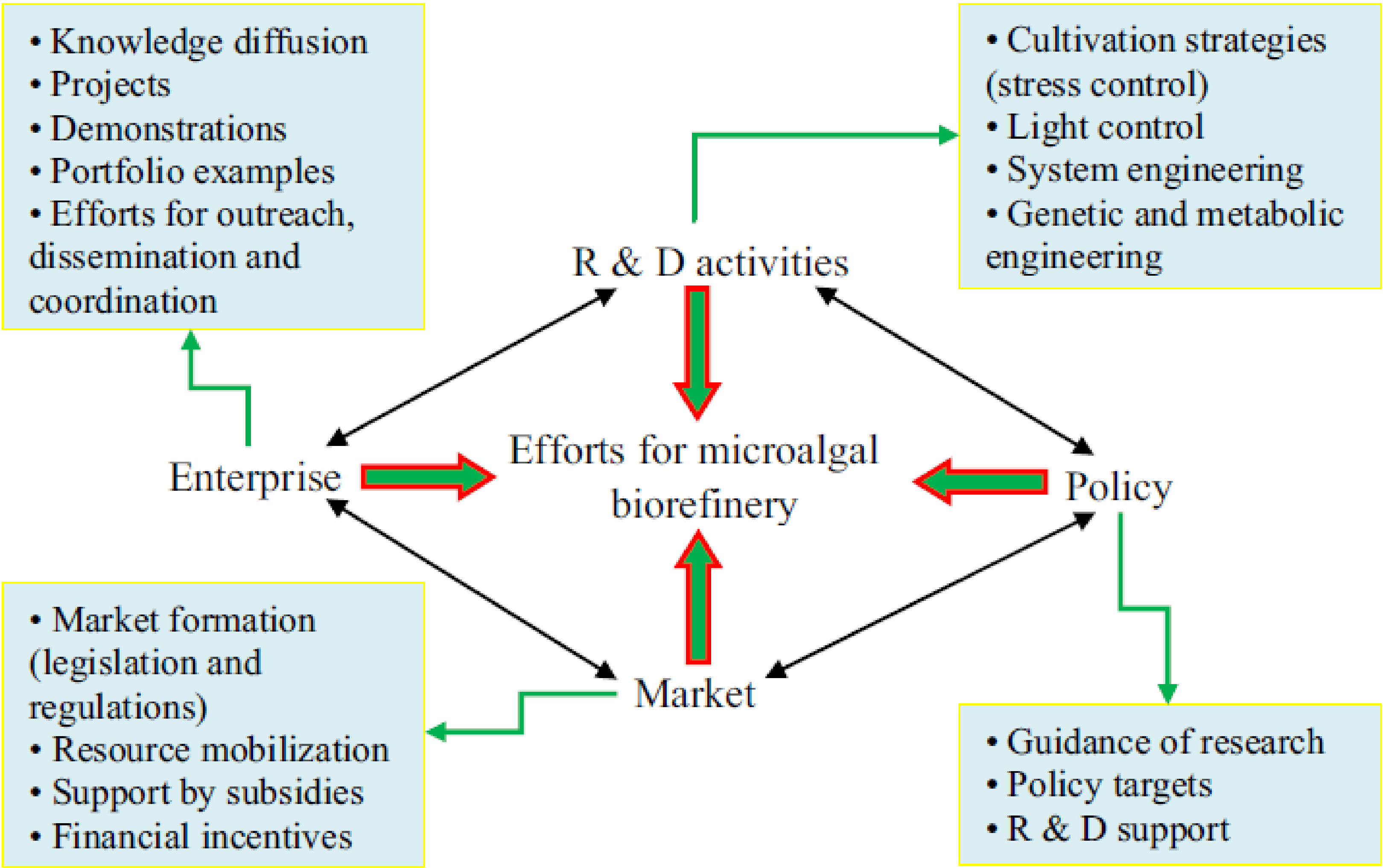
M.L.N.M. Carneiro et al. Renewable and Sustainable Energy Reviews 73 (2017) 632–653

LCA comparaison for the 3 biofuels generation in terms of NER and ERIO



M.L.N.M. Carneiro et al. Renewable and Sustainable Energy Reviews 73 (2017) 632–653

Efforts required for economic viability and systainibility of 3G bioreffinery and biofuel production



Exemples of inducers to increase the content of interesting biochemical compounds

L.M. Schüler et al. Algal Research 25 (2017) 263–273

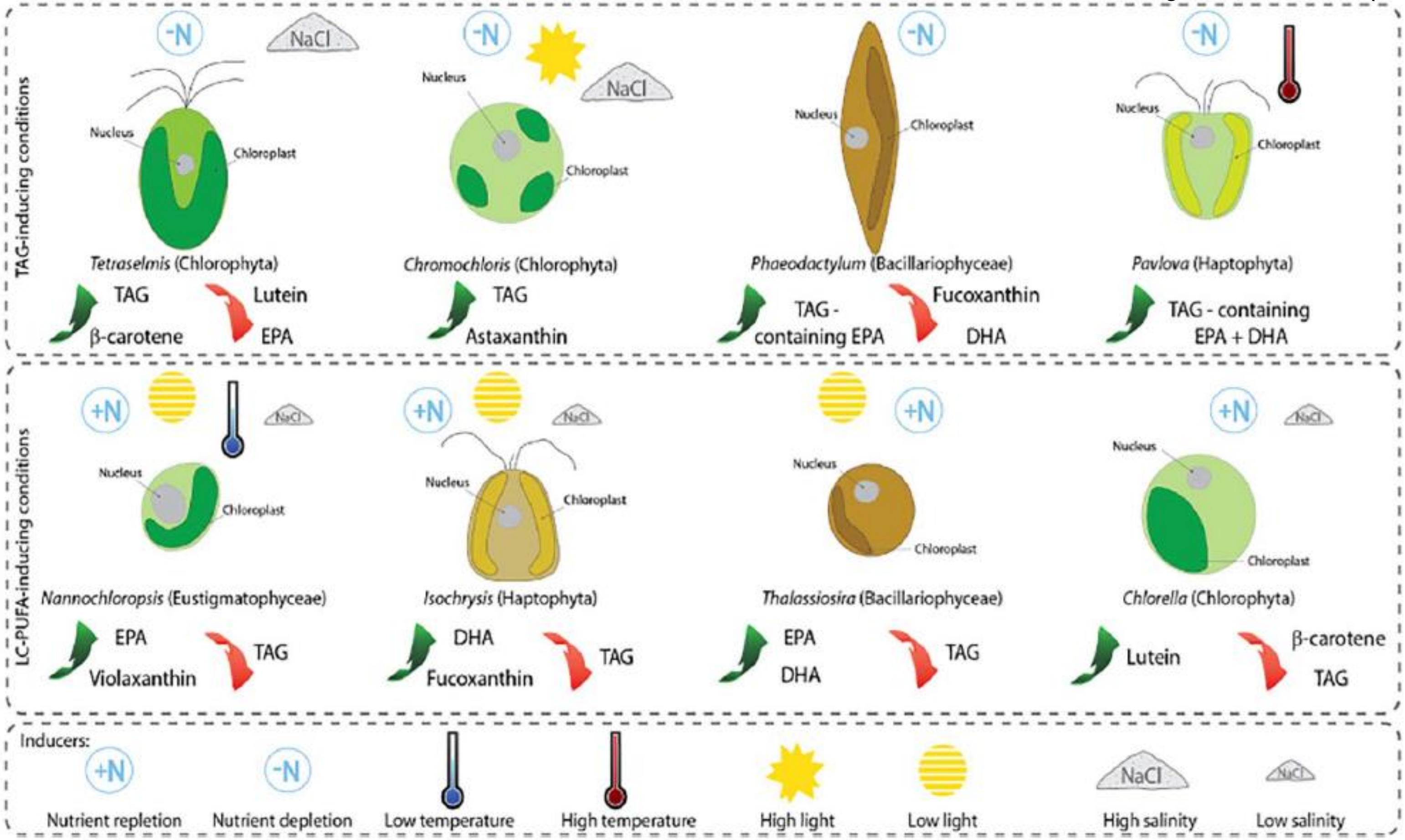


Fig. 4. Simplified illustration of microalgal species with their relative content of TAGs, LC-PUFAs and carotenoids upon exposure to different inducers applied alone or in combination. In the upper panel TAG-inducing stressor such as nutrient depletion, high temperature, high light and high salinity are shown, whereas stressors such as low temperature, low light and nutrient replete conditions usually lead to elevated LC-PUFA contents as represented in the lower panel.

Conclusions

Plus	Minus
• High surface productivity • Flexible Composition of biomass • Limited competition on food production • Urban and industrial effluents and waste recycling (N, P, … wastewater) or cement plant/power station (CO_2))	• Use of stress conditions to induce the storage of energy-rich compounds • Expensive harvesting and drying processes • Little genetic improvement

	Microalagae	C3 plants	C4 plants (Sorghym, corn)
Maximum productivity ($T.ha^{-1}.year^{-1}$)	150-180	30	60
Observed productivity ($T.ha^{-1}.year^{-1}$) (PBR/Field)	50-70	10-15	10-30

Strengths and difficulties of the microalgal sector in large scale production

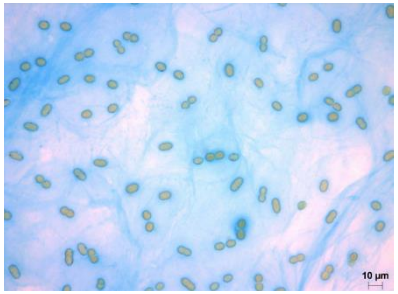
Sectors	Applications, potential	Strengths	Difficulties
Environment	• CO_2 remediation • Effluent treatment (ponds/raceway)	• N, P, CO_2 consumption • Existing pond/raceway	• Effluents polluted with toxic compounds
Energy	• Biodiesel • Bio-crude oil • Biogas	• High lipids contents (7 to 30 higher than rapeseed) • No competition with food • Co-products valorisation	• Large scale production • Industrial technology • Large area needed
Fish Farming	• Quality food (proteins, • omega 3)	• First level of the aquatic food chain • Nutritional quality	• Need of « non polluted » substrates for the culture • Single species culture required
Feed	• Livestock • Pet	• Co-products valorisation • Protein intake • Reduced dependence on soy	• Large scale production • Industrial technology
Green chemistry Bio-material	• Bio-polymers • Lipo-chemistry	• New raw materials for bioplastics and agrosurfactants	• Large scale production • Industrial technology

Adapted from Adebiotech. Livre turquoise, 2010

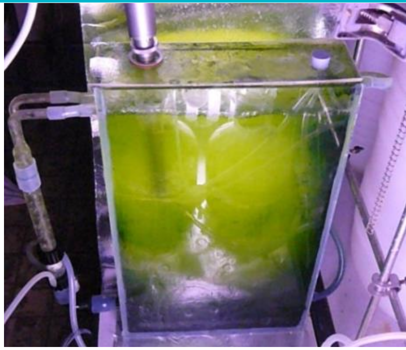
Strengths and difficulties of the microalgal sector in high value added markets

Sectors	Applications, potentials	Strengths	Difficulties
Cosmetics	• Active compounds, dyes/colorants, antioxidants	• Innovative natural compounds, • high diversity of species and molecules, • rich in antioxidants, • good marketing image	• Few cultivated species at large scale, • low dry matter content in the culture medium, • evolution of the regulations
Food supplements Nutraceutical	• Omega 3 • Carotenoids • Proteins	• Important nutritional quality (omega 3, vitamins, proteins), • existing markets	• Long and complex regulations, • high production costs, • almost incompatible CO_2 remediation, • Market control
Human health	• Control Diagnosis	• Very high added value, • replaces the use of radioactive products	• Niche market, • impossible CO_2 remediation, • Long regulations
Human Food	• Food, • Colorants, Ingridents	• Nutritional qualities, • Natural colorants, • Fight undernitrition	• Long and complex regulations, • Consumer acceptability

Adapted from Adebiotech. Livre turquoise, 2010



Conclusions



Environmental Microalgal Biorefinery

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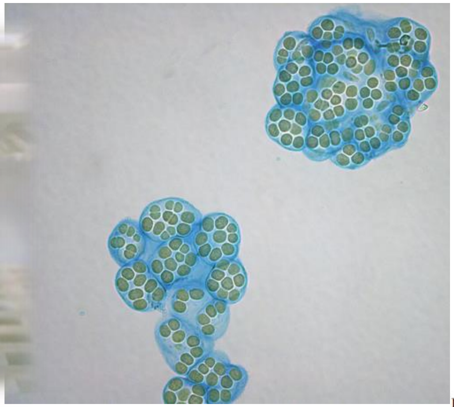
Real Opportunity for integrated biosourced products and biofuels developments



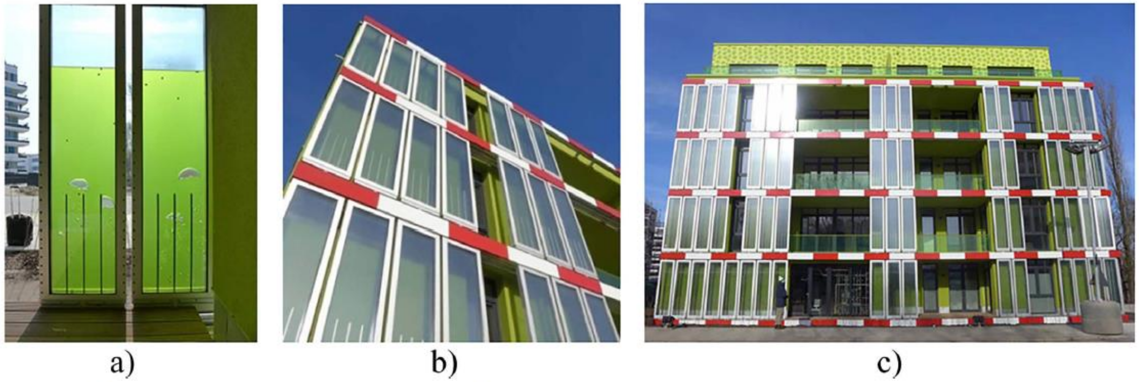
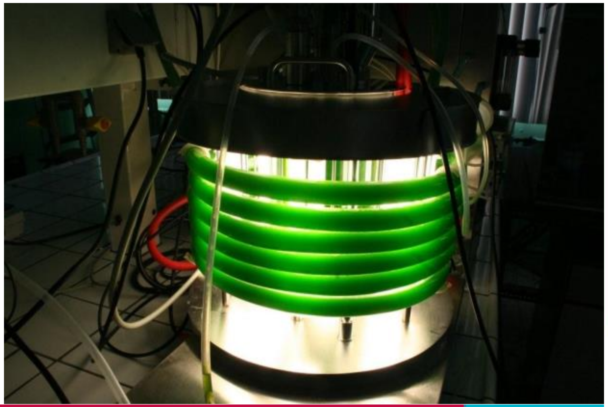
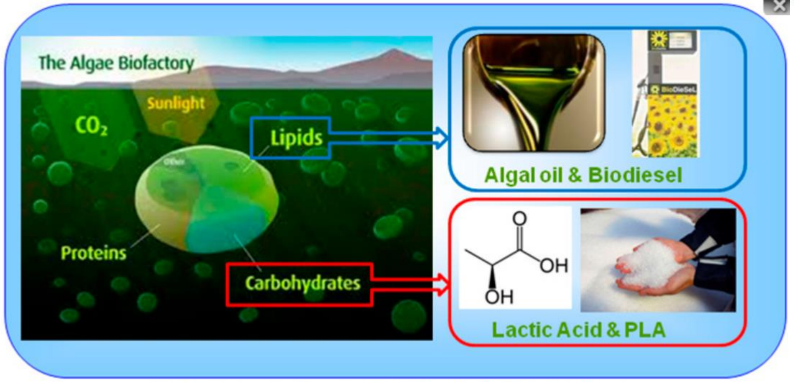
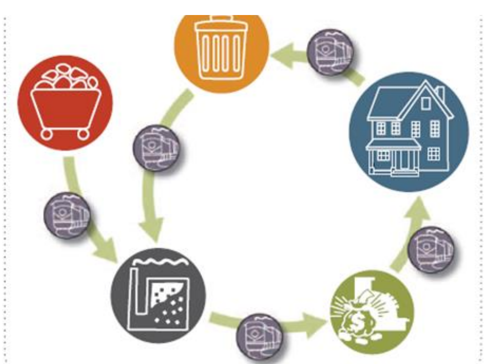


Fig. 3. *The BIQ building, the first algae-powered building by Arup* (© Colt International, Arup Deutschland, SSC GmbH).





The double purpose algae approach for biodiesel and lactic acid production.



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Thank for your attention