ETH zürich

SFP SUSTAINABLE FOOD PROCESSING

Emerging food production and processing for more sustainable food systems

Parma Summer School 2023

Prof. Dr.-Ing. Alexander Mathys
ETH Zurich

OUR CULTIVATED PLANET

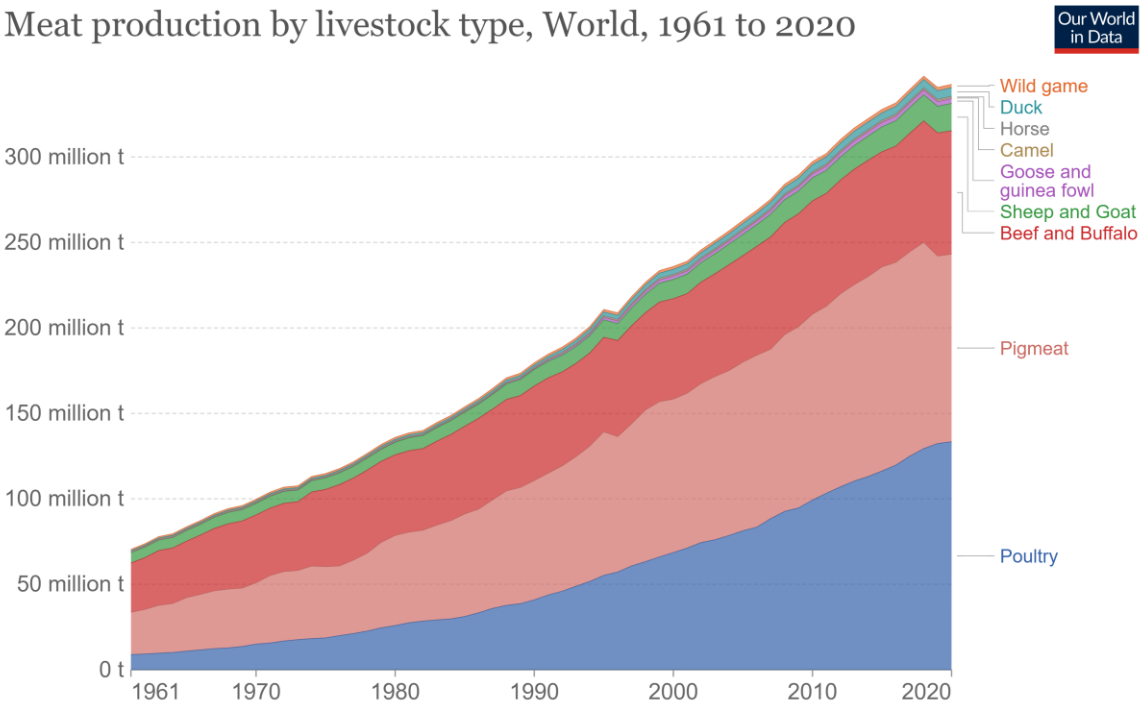
This table shows **the ten most cultivated crops of the world**. Of 1,400 million hectares (Mha) of arable land, more than a third is covered by the three major cereals: wheat, maize and rice. Soybeans are the only other crop to be grown on more than 100 Mha, with strong growth over the last 20 years, while other crops covers much smaller areas. Although they do not always have the highest yields, the largest countries (United States, China, Russia, India, etc.) are the main grain producers, with more or less regional specificities depending on the crop.

Crops[1]	Surface and Yield evolution[2]	Main producers
1. Wheat (216 Mha) Originally from the Fertile Crescent, in the Middle East, wheat is now the most cultivated cereal in the world	150%, 125%, 2005, 2015	
2. Maize (197 Mha) Corn, first cultivated in Central America, is now widely grown but, unlike wheat, it cannot be grown in the coldest regions	150%, 125%, 2005, 2015	
3. Rice (162 Mha) Rice is the world' s third major cereal but, unlike wheat, it is still mostly grown in its historical area of origin: Asia.	150%, 125%, 2005, 2015	
4. Soybeans (121 Mha) Soy is the first legume cultivated in the world. Soy is mainly cultivated in America and exported all over the world, mainly for cattle feed	150%, 125%, 2005, 2015	
5. Barley (51 Mha) Barley is mainly grown in temperate regions. It has two main usages: malting and cattle feeding.	150%, 125%, 2005, 2015	

[1] The areas occupied by each crop as well as the maps of the quantity produced by each country refer to year 2019.

[2] Trends from 2000 to 2019, expressed as percentage of values for year 2000

Data: FAOStats | **Table:** @BjnNowak



Source: UN Food and Agricultural Organization (FAO) OurWorldInData.org/meat-production • CC BY
Note: Total meat production includes both commercial and farm slaughter. Data are given in terms of dressed carcass weight, excluding offal and slaughter fats.

Farmed animals: 1.5 bn cattle, 1 bn pigs, 19 bn chicken
Slaughtered per year: 69 bn chicken, 1.5 bn pigs, 302 million cattle
WEF, 2019; Our World in Data, 2022

Pets in the world: 470 million dogs, 370 million pet cats.
https://www.statista.com

Recent Relevant Publications on Food System Sustainability

THE LANCET
Planetary Health

Articulating the effect of food systems innovation on the Sustainable Development Goals

Mario Herrero, Philip K Thornton, Daniel Mason-D'Croz, Jeda Palmer, Benjamin L Bodirsky, Prajal Pradhan, Christopher B Barrett, Tim G Benton, Andrew Hall, Ilje Pikaar, Jessica R Bogard, Graham D Bonnett, Brett A Bryan, Bruce M Campbell, Svend Christensen, Michael Clark, Jessica Fanzo, Cecile M Godde, Andy Jarvis, Ana Maria Loboguerrero, Alexander Mathys, C Lynne McIntyre, Rosamond L Naylor, Rebecca Nelson, Michael Obersteiner, Alejandro Parodi, Alexander Popp, Katie Ricketts, Pete Smith, Hugo Valin, Sonja J Vermeulen, Joost Vervoort, Mark van Wijk, Hannah HE van Zanten, Paul C West, Stephen A Wood, Johan Rockström

nature sustainability

comment | Check for updates

Bundling innovations to transform agri-food systems

Christopher B. Barrett, Tim G. Benton, Karen A. Cooper, Jessica Fanzo, Rikin Gandhi, Mario Herrero, Steven James, Mark Kahn, Daniel Mason-D'Croz, Alexander Mathys, Rebecca J. Nelson, Jianbo Shen, Philip Thornton, Elizabeth Bageant, Shenggen Fan, Andrew G. Mude, Lindiwe M. Sibanda and Stephen Wood

ENVIRONMENTAL RESEARCH LETTERS

PERSPECTIVE

COVID-19 pandemic lessons for agri-food systems innovation

Christopher B Barrett, Jessica Fanzo, Mario Herrero, Daniel Mason-D'Croz, Alexander Mathys, Philip Thornton, Stephen Wood, Tim G Benton, Shenggen Fan, Laté Lawson-Lartego, Rebecca Nelson, Jianbo Shen and Lindiwe Majele Sibanda

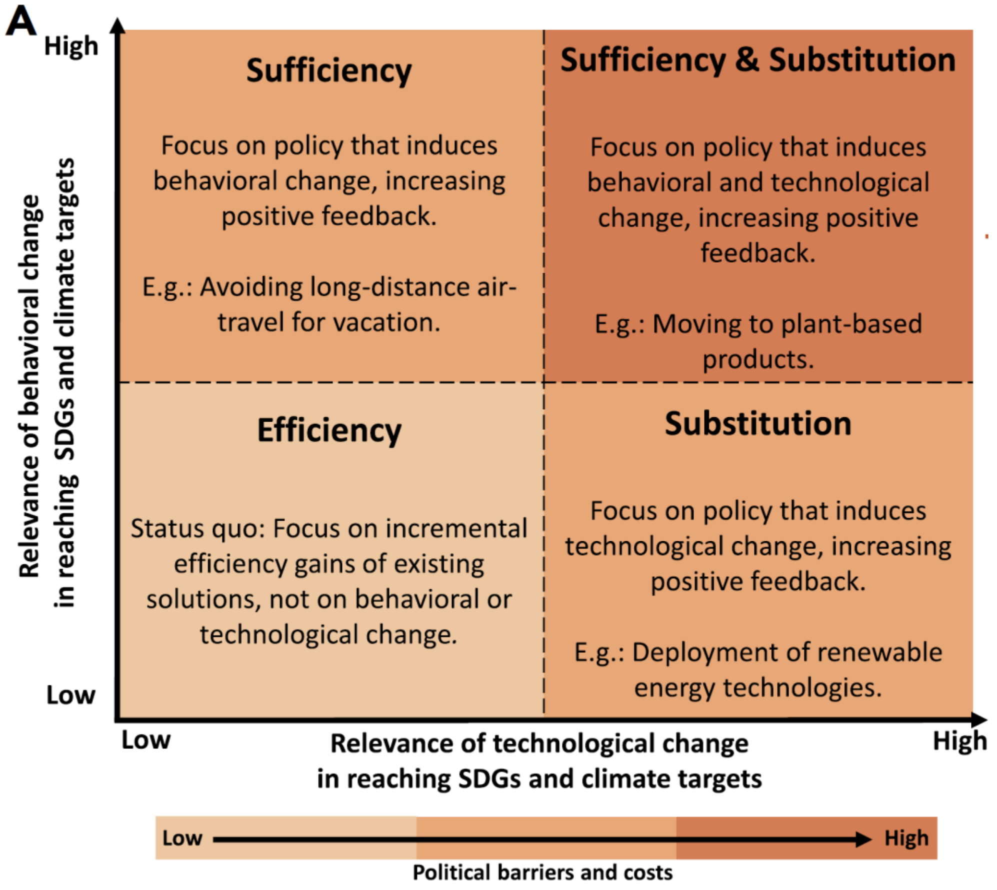
Socio-Technical Innovation Bundles for Agri-Food Systems Transformation

A Cornell Atkinson Center for Sustainability/ Nature Sustainability Expert Panel Report

December 2020

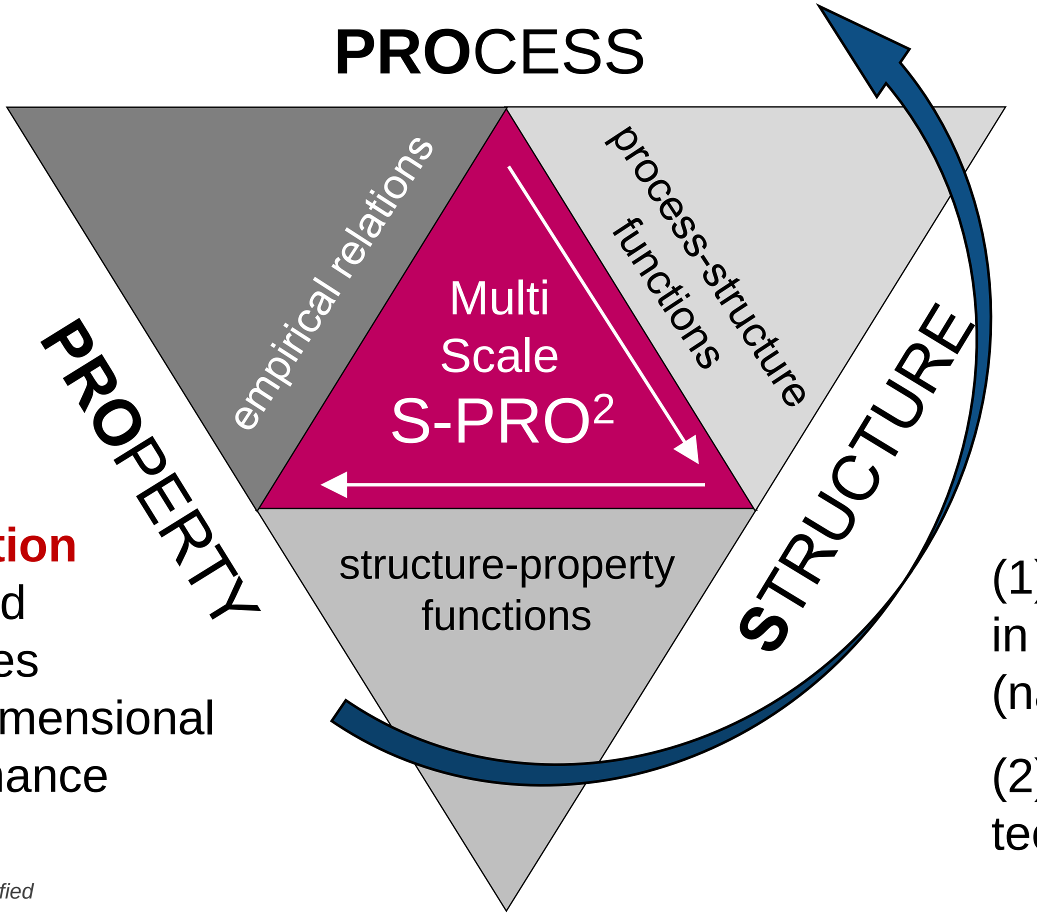
nature sustainability

The relevance of behavioral and technological changes for developing enabling policy strategies for sustainable development



Fesenfeld, Schmid, Finger, Mathys & Schmidt (2022). One Earth https://doi.org/10.1016/j.oneear.2022.09.004

Reverse Engineering Approach



Which is the **structure** providing the target properties & which is the **process** to generate such structure

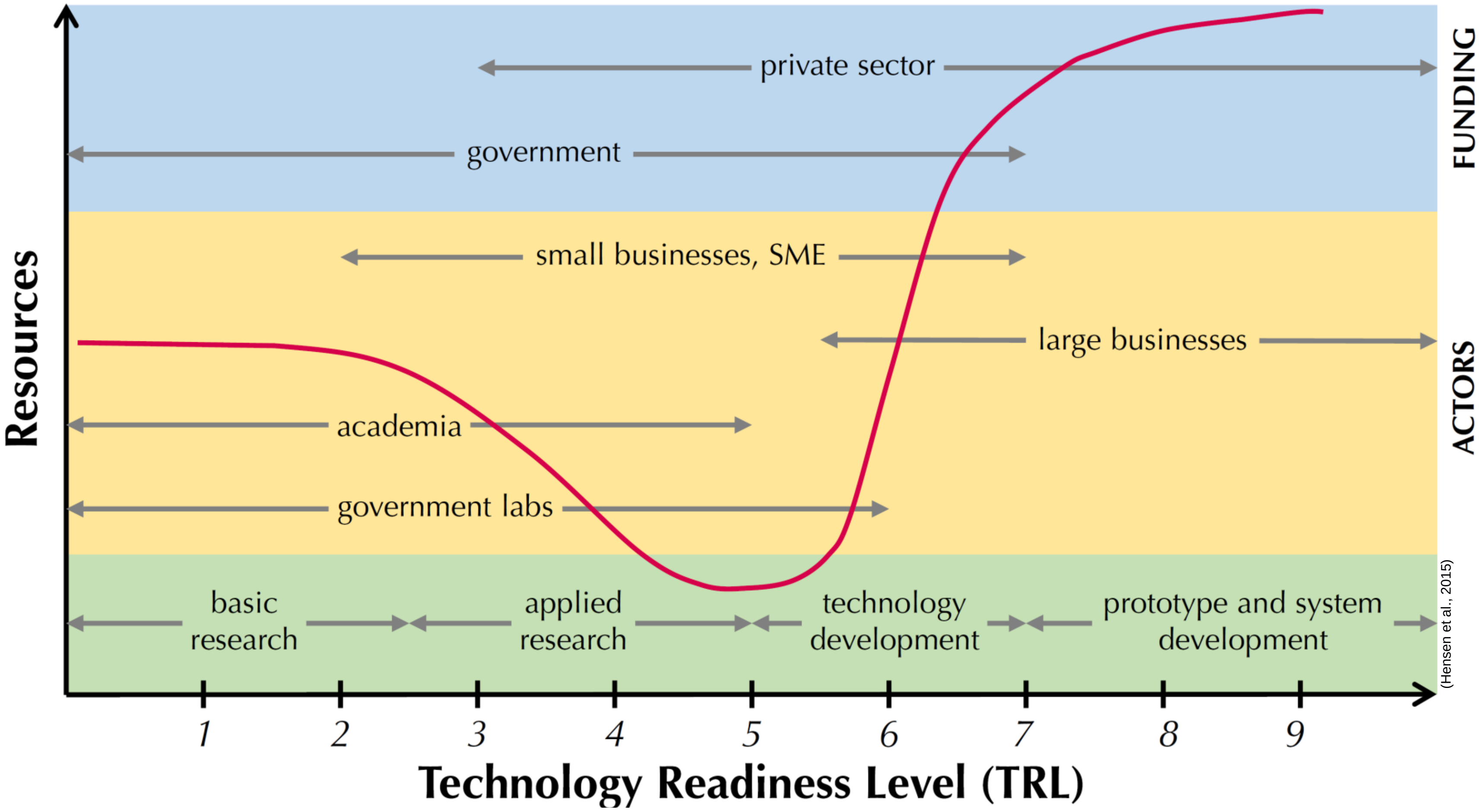
(1) Affordable Nutrition
(2) Consumer focused organoleptic properties
(2) Improved three dimensional sustainability performance

(1) Targeted (multiphase) structure in different scales (nano, micro, meso, macro)

(2) Materials with targeted techno- and biofunctionalities

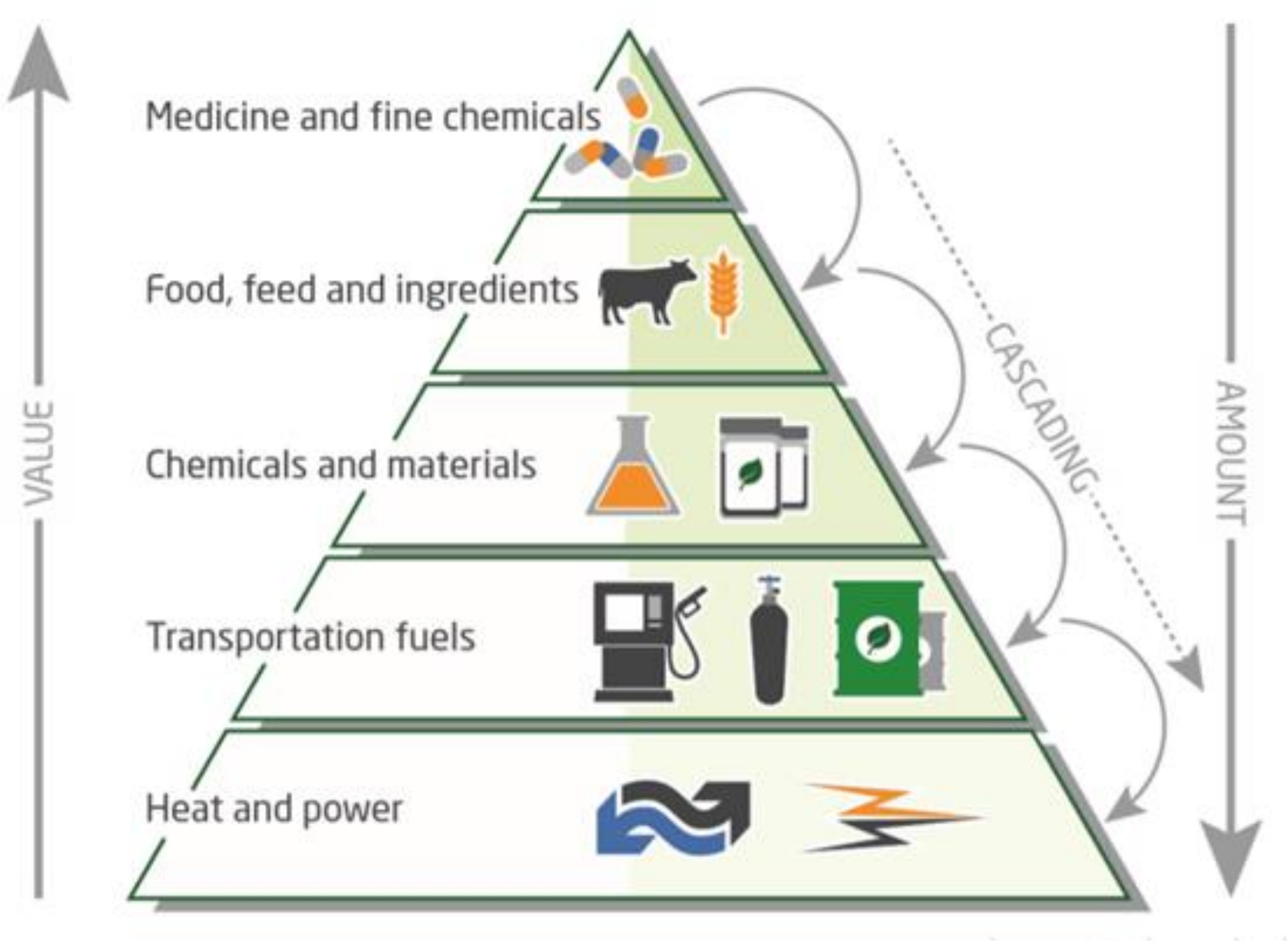
S-PRO2 model from Windhab; adapted and modified

Different technology readiness level, the connected ecosystem and relevance of economies of scale



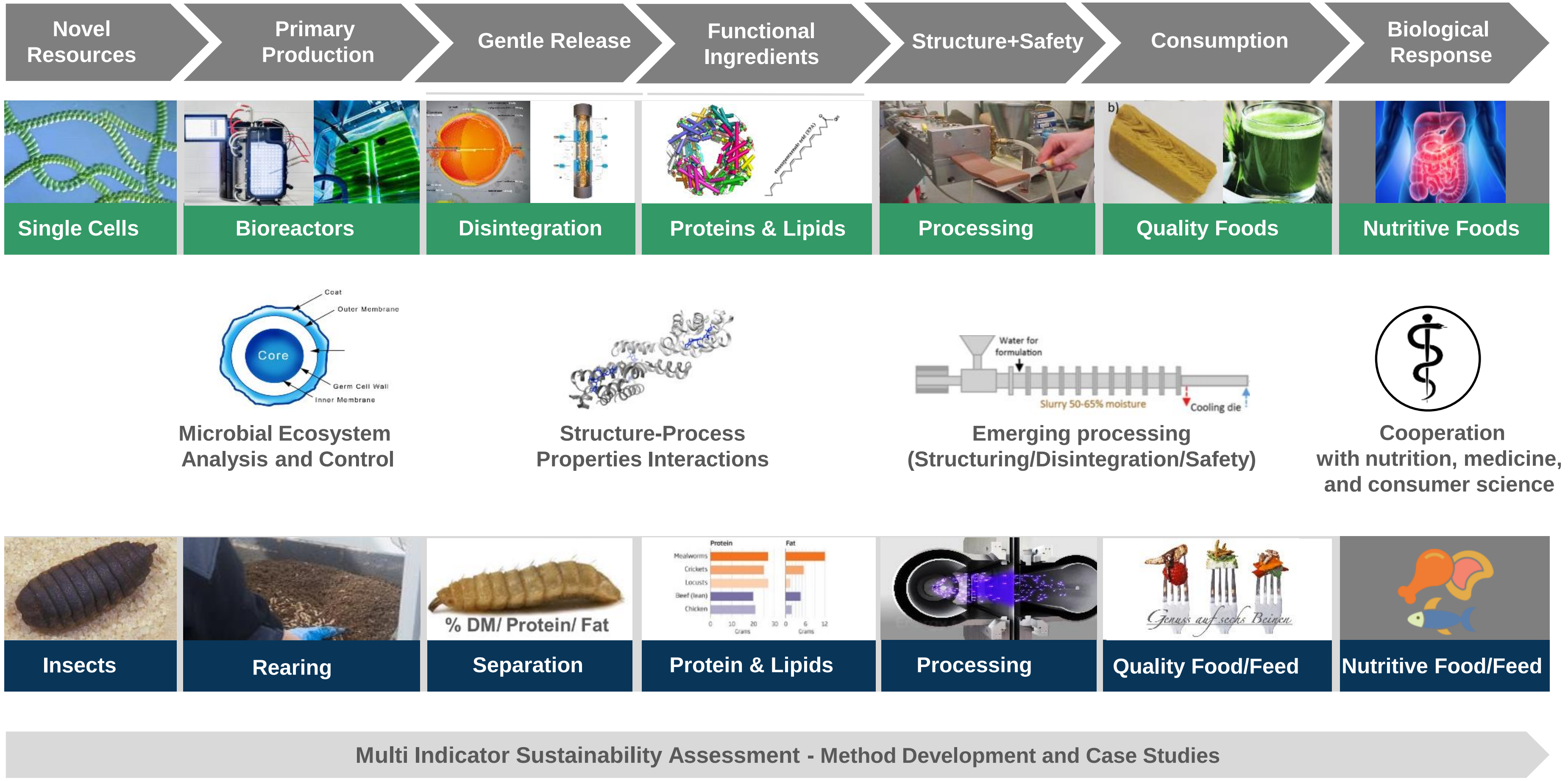
+

Biomass Value Pyramid

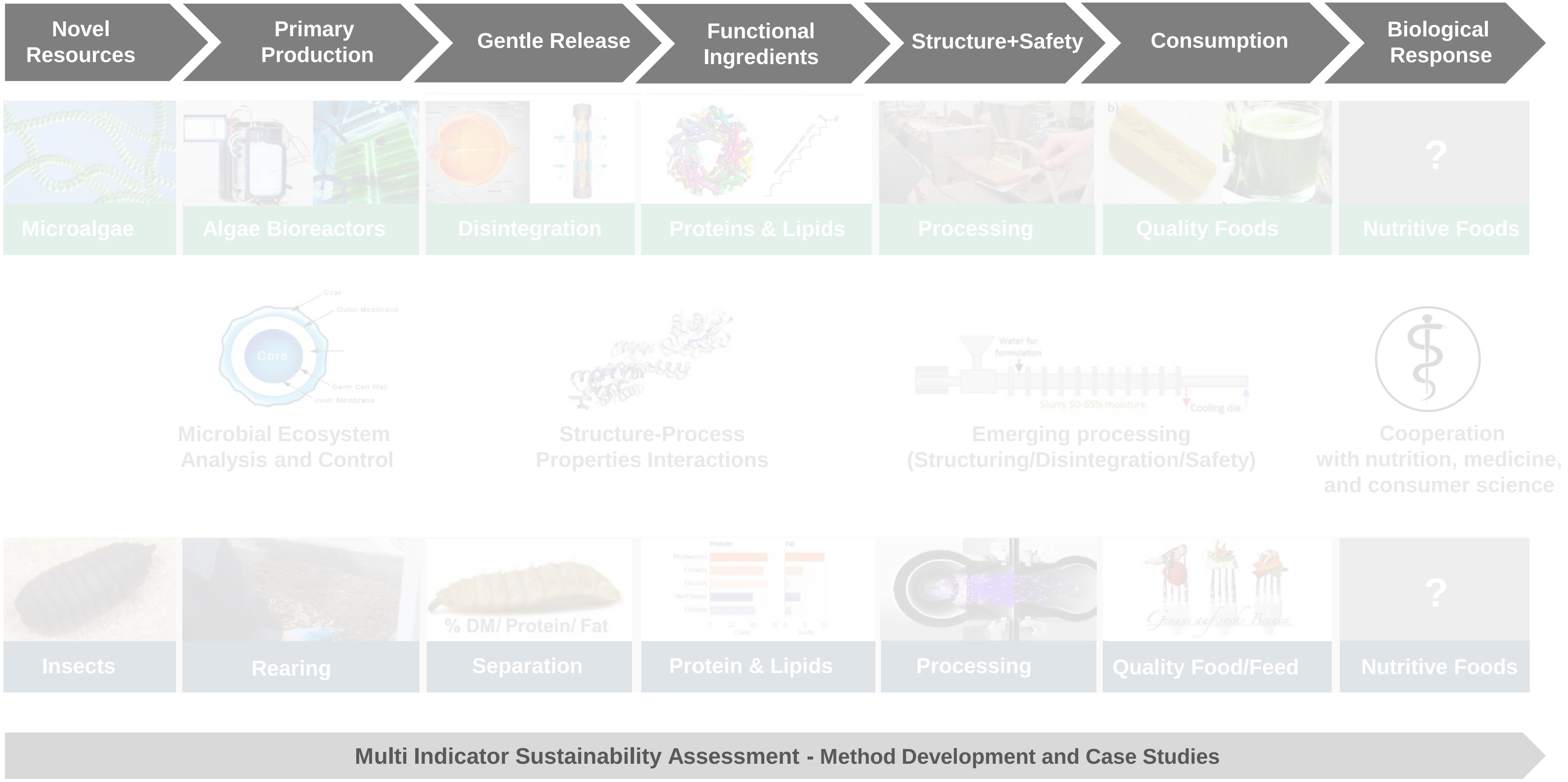


https://frsfarmreliefservices.ie

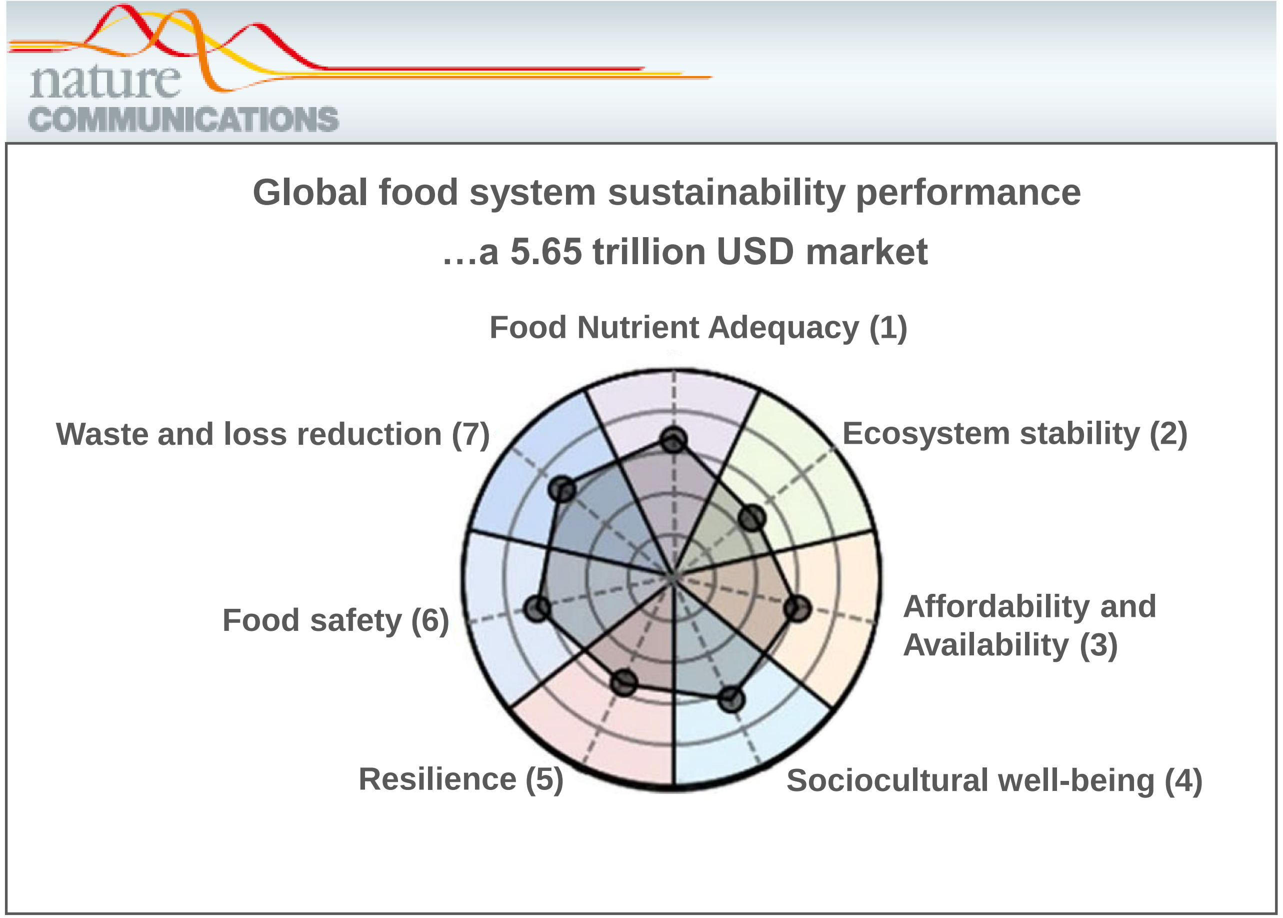
ETH Sustainable Food Processing Research



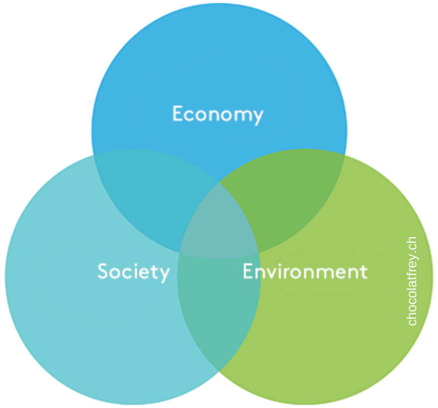
ETH Sustainable Food Processing Research-Focus Sustainability



Food system understanding by multi-indicator sustainability analysis of all three dimensions



Chaudhary, Gustafson & Mathys 2018, Nature Communications. 9, 848



FNSNF
73 NRP Sustainable Economy
National Research Programme

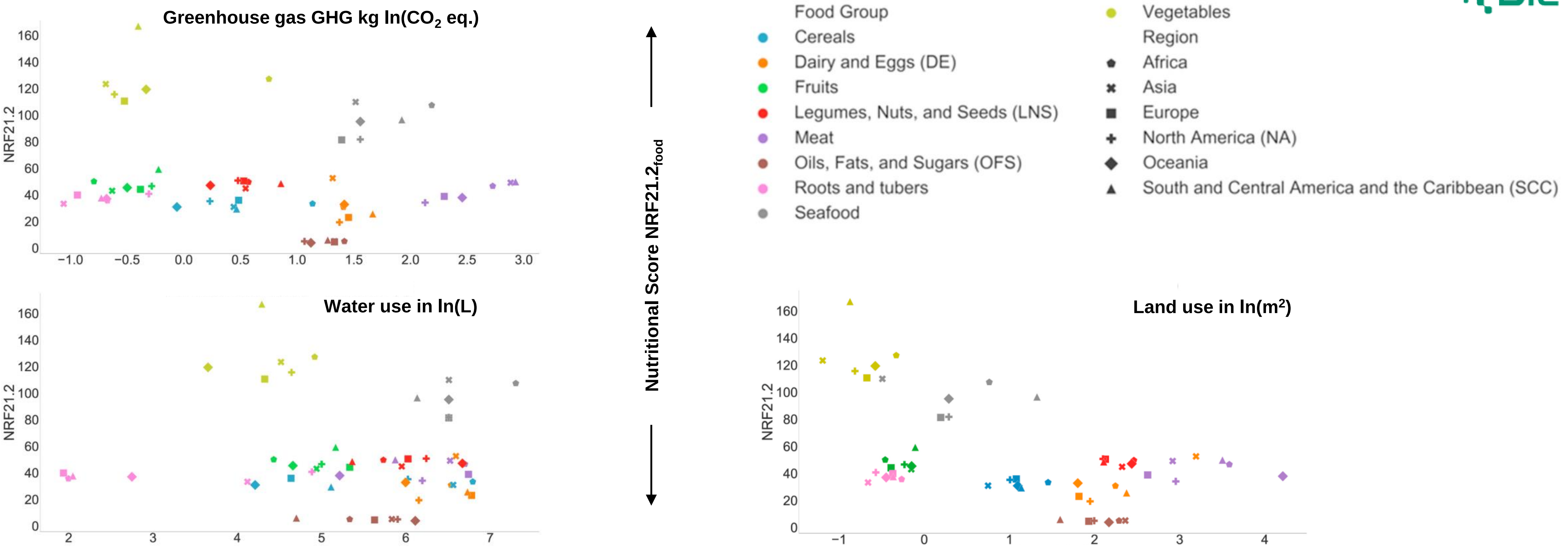
Global food systems are at the heart of our 17 SDGs

(United Nations, 2015)

Multi Indicator Sustainability Assessment - Regionally-explicit nutritional scores (Nutrient Rich Food Index NRF21.2_{food}) & mass-based (1 kg) environmental impacts

Agroscope

DIL



Green, Nemecek, Smetana & Mathys, 2021, Journal of Cleaner Production, 312, 127696

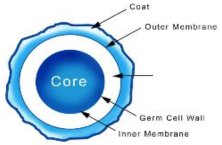
Shows nutritionally-invested environmental impacts

ETH Sustainable Food Processing Research-Focus Insects

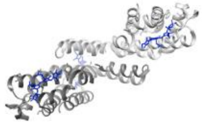
SFP

Novel Resources → Primary Production → Gentle Release → Functional Ingredients → Structure+Safety → Consumption → Biological Response

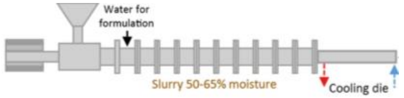
Microalgae | Algae Bioreactors | Disintegration | Proteins & Lipids | Processing | Quality Foods | Nutritive Foods



Microbial Ecosystem Analysis and Control

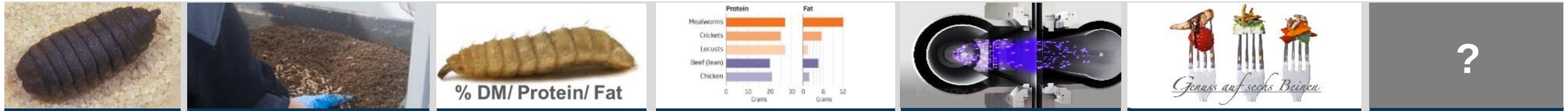


Structure-Process Properties Interactions



Emerging processing (Structuring/Disintegration/Safety)

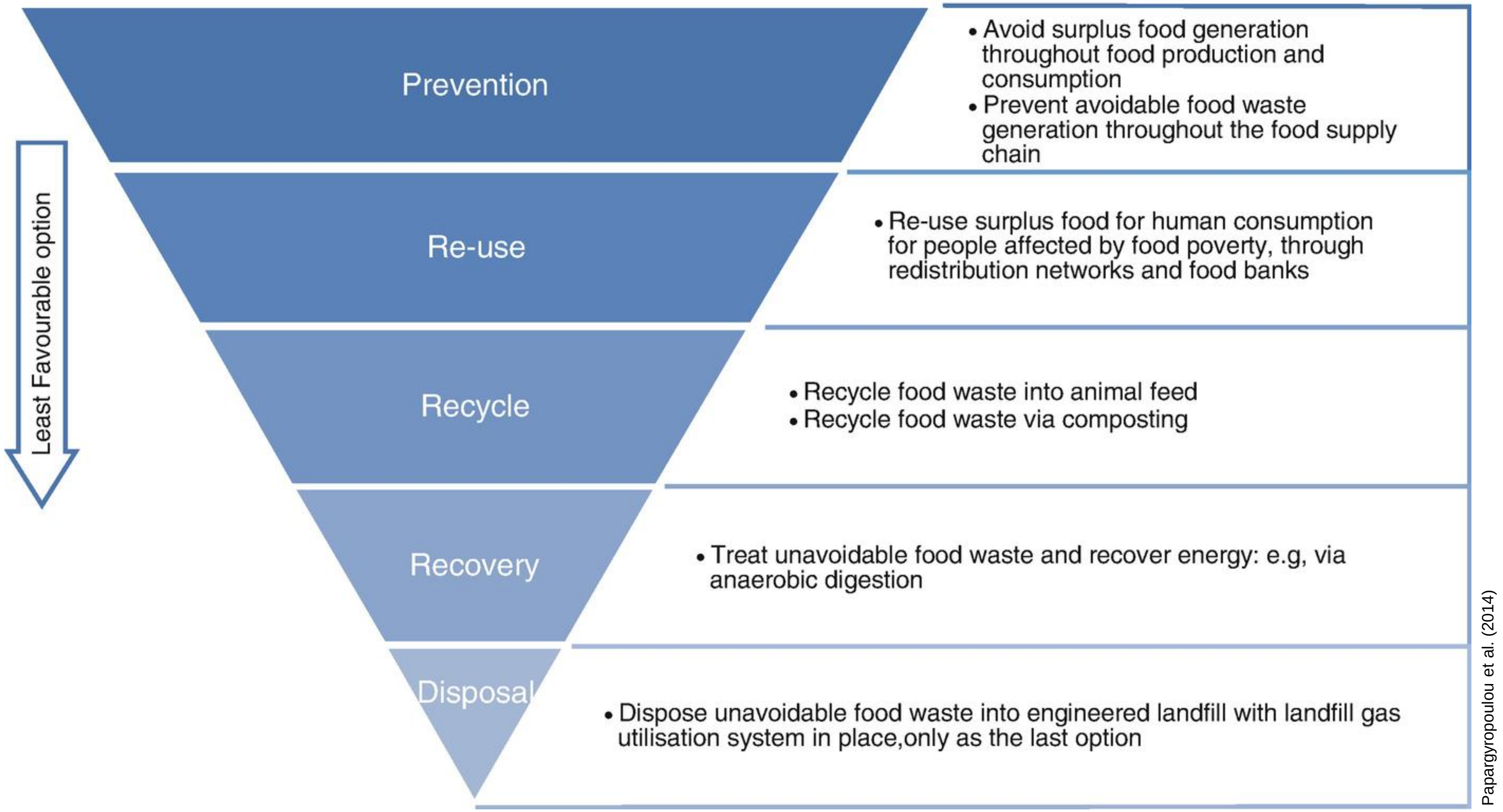
Cooperation with nutrition, medicine, and consumer science



Insects | Rearing | Separation | Protein & Lipids | Processing | Quality Food/Feed | Nutritive Food

Multi Indicator Sustainability Assessment - Method Development and Case Studies

The Waste hierarchy from most favourable to least favourable actions



(Hansen, Wenke; Christopher, Maria; Verbuecheln, Maic 2002. EU Waste Policies and Challenges for Local and Regional Authorities)

Waste hierarchy
is a tool used in the evaluation of processes that protect the environment alongside resource and energy consumption from most favourable to least favourable actions

Alternative animal proteins based on Black Soldier Fly waste utilization for more sustainable feeds

(Stefan Diener, Black Soldier Fly Biowaste Processing Manual, Sandec 2017; ETH Zurich SFP and Eawag facility in Dübendorf, CH)

1) Gold,Tomberlin, Diener, Zurbrügg, & Mathys (2018). Waste Management. 82, 302-318.
2) Aarts, Jansen, Jacobs, Mescher, Prenter, Mathys & De Moraes (2018). Processing of insect larvae. EU patent application. Application No 18175914.3-110
3) Gold, Cassar, Zurbrügg, Kreuzer, Bolus, Diener & Mathys (2019). Waste Management. 102, 319-329.
4) Gold, Egger, Scheidegger, Zurbrügg, Bruno, Bonelli, Tettamanti, Casartelli, Schmitt, Kerkaert, De Smet, van Campenhout & Mathys (2020). Waste Management. 112, 40-51.
5) Gold et al. (2020). Journal of Insect Science, 20: 3, 21ff.
6) Gold, von Allmen, Zhang, Zurbrügg & Mathys (2020). Frontiers in Microbiology, 11: 582867.
7) Gold, Fowles, Fernandez-Bayo, Palma Miner, Zurbrügg, Nansen, Bischel & Mathys (2021). Journal of Insects as Food and Feed. doi.org/10.3920/JIFF2021.0038
8) Peguero, Gold, Vandeweyer, Zurbrügg & Mathys (2021). Frontiers Sustainable Food Systems.

Black soldier fly larvae-based side stream and waste utilization and biorefinery products

BÜHLER

PROTIX

Protein meal

Key benefits: Balanced amino acid profile with very good palatability and digestibility.

Insect lipids

Key benefits: Easy digestible energy with high lauric acid content.

Fertilizer

Key benefits: Slow nutrient release over time with chitin as functional component.

(BITS, 2020)

Smetana, Schmitt & Mathys (2019). Resources, Conservation & Recycling. 144, 285–296.

Develop processes for the BSF larvae to utilize food waste using novel machine learning approaches in larval rearing

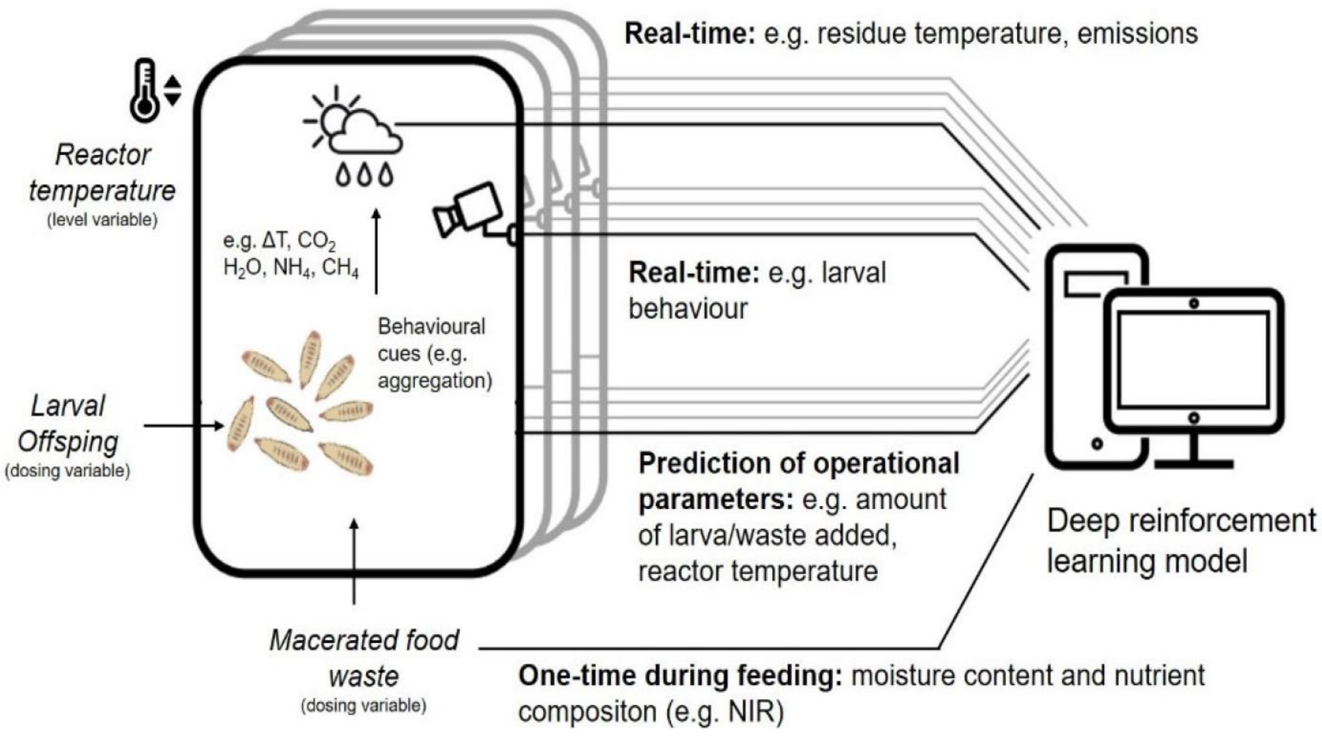


Figure 3: Design for decentralized BSF rearing. Adjusting of operational parameters (e.g. larval number, temperature) by sensor-based performance indicators.

NUS National University of Singapore (SEC) SINGAPORE-ETH CENTRE

THE STRAITS TIMES

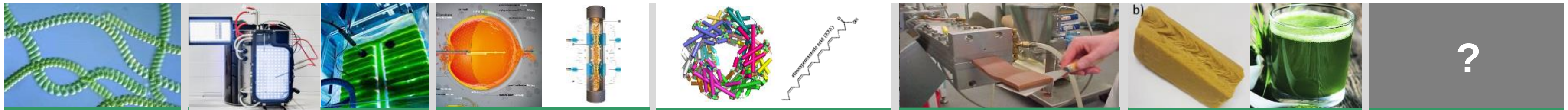
Researchers develop blueprint for sustainable food system using black soldier flies

(From left) Professor Stephen Cairns, Assistant Professors Alexander Mathys and Nalini Puniamoorthy on Jan 25, 2022. ST PHOTO: JASON QUAH

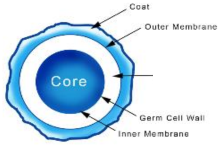
https://news.nus.edu.sg/interdisciplinary-team-to-develop-blueprint-for-sustainable-urban-food-waste-management-and-food-systems-using-black-soldier-flies/

ETH Sustainable Food Processing Research-Focus Microalgae

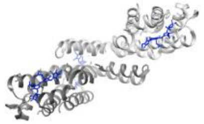
Novel Resources → Primary Production → Gentle Release → Functional Ingredients → Structure+Safety → Consumption → Biological Response



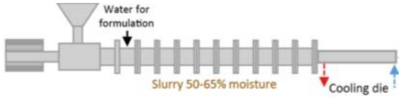
Microalgae	Algae Bioreactors	Disintegration	Proteins & Lipids	Processing	Quality Foods	Nutritive Foods



Microbial Ecosystem Analysis and Control



Structure-Process Properties Interactions



Emerging processing (Structuring/Disintegration/Safety)

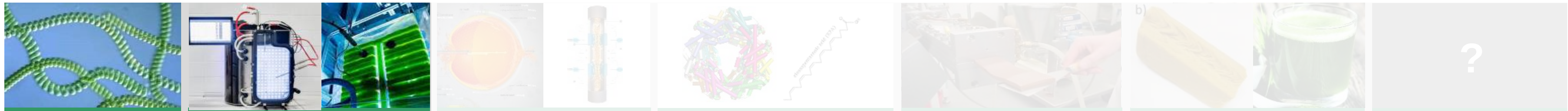
Cooperation with nutrition, medicine, and consumer science

Insects	Rearing	Separation	Protein & Lipids	Processing	Quality Food/Feed	Nutritive Foods

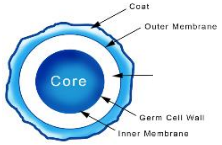
Multi Indicator Sustainability Assessment - Method Development and Case Studies

ETH Sustainable Food Processing Research-Focus Microalgae

Novel Resources → Primary Production → Gentle Release → Functional Ingredients → Structure+Safety → Consumption → Biological Response



Microalgae | Algae Bioreactors | Disintegration | Proteins & Lipids | Processing | Quality Foods | Nutritive Foods



Microbial Ecosystem Analysis and Control

Structure-Process Properties Interactions

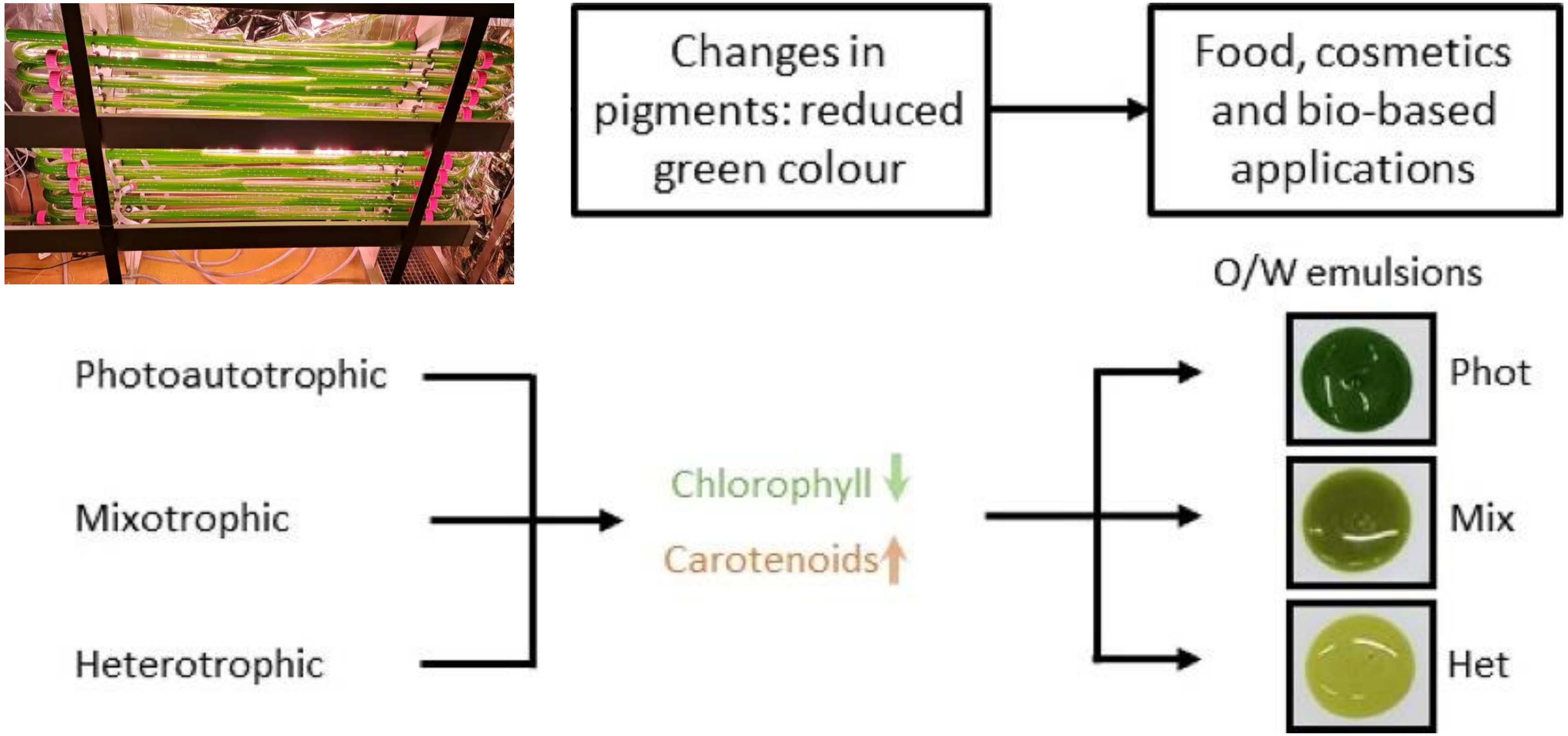
Emerging processing (Structuring/Disintegration/Safety)

Cooperation with nutrition, medicine, and consumer science

Insects | Rearing | Separation | Protein & Lipids | Processing | Quality Food/Feed | Nutritive Foods

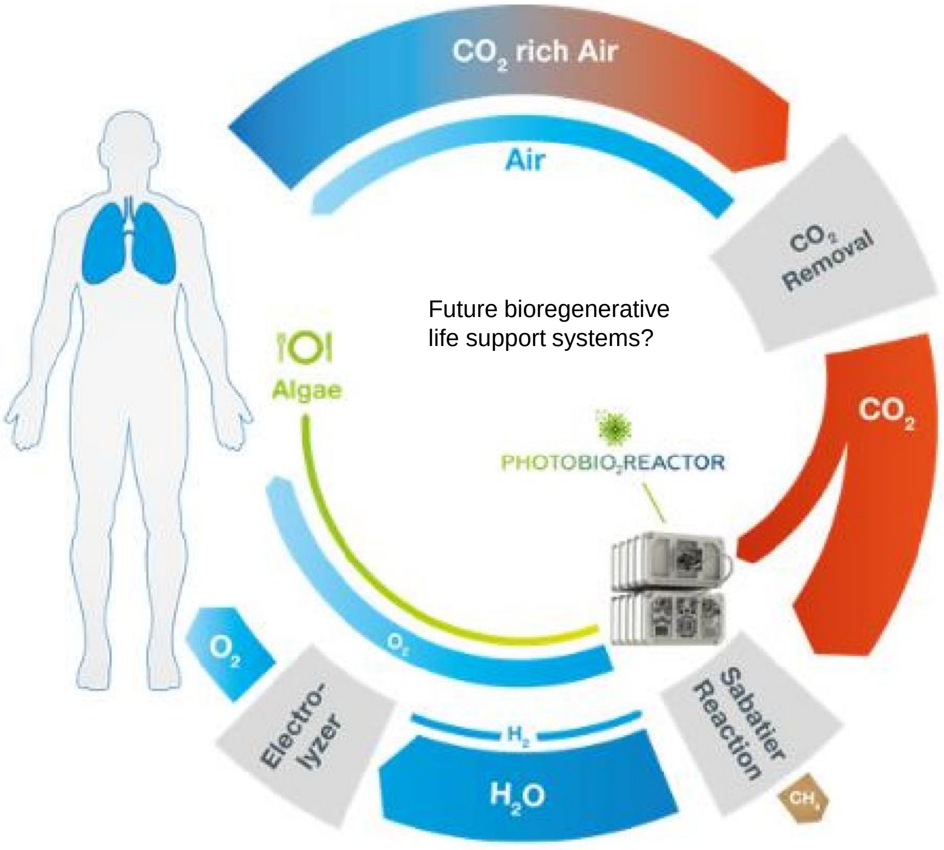
Multi Indicator Sustainability Assessment - Method Development and Case Studies

Innovative microalgae upstream cultivation to increase efficiency and adapt final composition, nutritional aspects, and color



Caporgno, Haberkorn, Böcker & Mathys (2019). Bioresource Technology, 288, 121476.

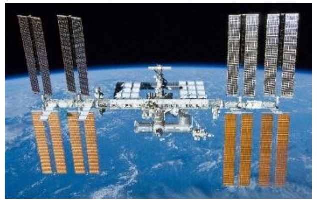
Chlorella vulgaris cultivation as life support system module onboard the International Space Station ISS



(IRS, 20167)

University of Stuttgart
Germany

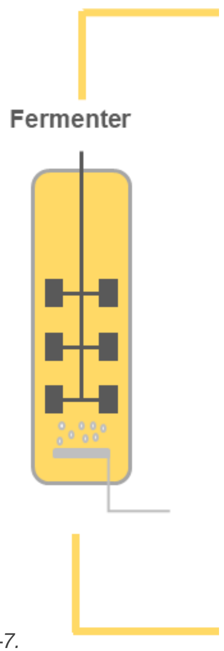
DLR Deutsches Zentrum für Luft- und Raumfahrt



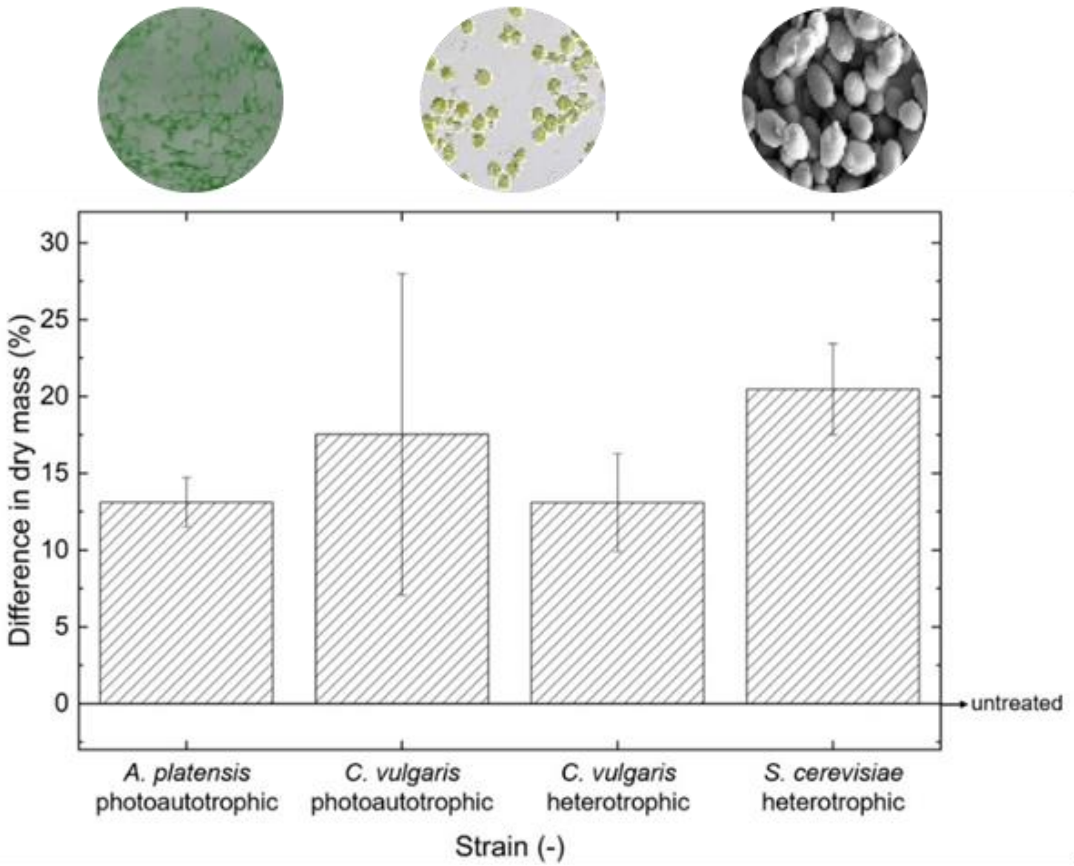
Alexander Gerst with *Chlorella* at ISS (ESA, 2018)

Haberkorn, Helisch, Belz, Detrell, Fasoulas & Mathys (2023), in preparation. Haberkorn (2021) Dr. thesis.
Haberkorn, Walser, Helisch, Böcker, Belz, Schuppler, Fasoulas & Mathys (2020). Journal of Phycology, 56: 1308 - 1322.

PEF-based microalgae process innovation – creating a holistic biorefinery



nsPEF-based growth stimulation <500 J/kg



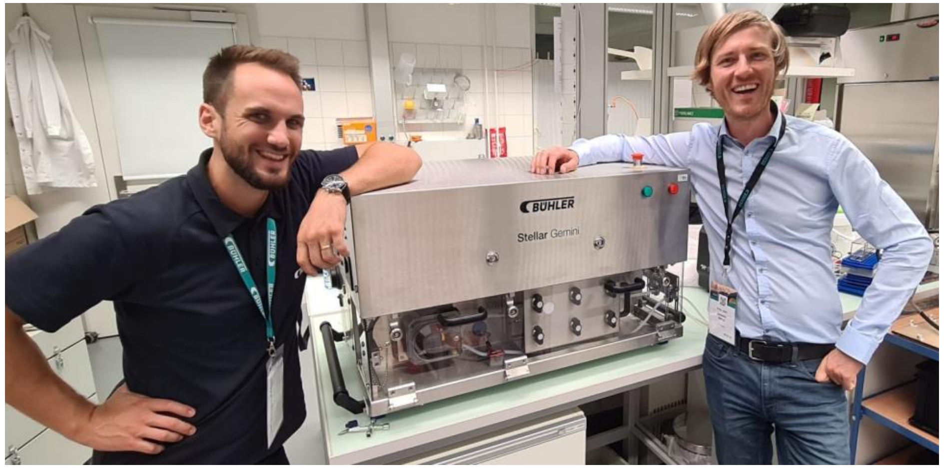
Buchmann & Mathys (2019). Frontiers in Bioengineering and Biotechnology, vol. 7, pp. 1–7.
Buchmann, Bloch & Mathys (2018). Bioresource Technology, vol. 265, pp. 268-274.
Buchmann, Böcker, Frey, Haberkorn, Nyffeler & Mathys (2018). Innovative Food Science and Emerging Technologies, vol. 47, pp. 445-453.
Buchmann, Frey, Gusbeth, Ravaynia & Mathys (2019). Bioresource Technology, vol. 271, pp. 402–408.
Buchmann, Brändle, Haberkorn, Hiestand & Mathys (2019). Bioresource Technology, vol. 291, pp. 121870.
Haberkorn, Buchmann, Hiestand & Mathys (2019). Bioresource Technology, vol. 293, pp. 122029.
Haberkorn, Buchmann, Häusermann & Mathys (2020). Bioresource Technology, vol. 319, pp. 124173.
Haberkorn, Siegenthaler, Buchmann, Neutsch & Mathys (2021). Biotechnology Advances.

Increased cell proliferation by nanosecond PEF
1st commercial system worldwide based on ETH Zurich R&D

ETH zürich Singapore-ETH Centre

About Research Impact People Partners News & Events Resources Jobs

Homepage > News & Events > ... 2022 > 08 > SEC's Microalgae project gets a stellar addition from its partner Bühler (



NEWS • RESEARCH PROJECT

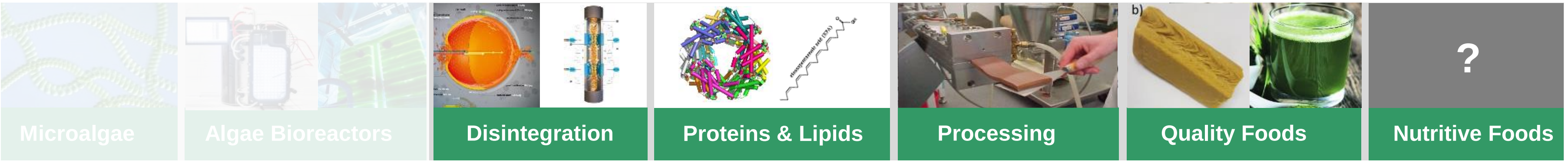
SEC's Microalgae project gets a stellar addition from its partner Bühler Group

Bühler Group deploys its world's first Stellar system based on nanosecond pulsed electric fields at SEC for more efficient microalgae processing.

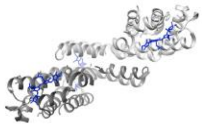
www. sec.ethz.ch

ETH Sustainable Food Processing Research-Focus Microalgae

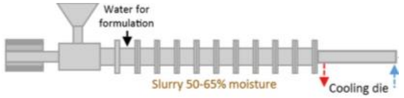
Novel Resources | Primary Production | Gentle Release | Functional Ingredients | Structure+Safety | Consumption | Biological Response



Microbial Ecosystem Analysis and Control



Structure-Process Properties Interactions



Emerging processing (Structuring/Disintegration/Safety)

Cooperation with nutrition, medicine, and consumer science

Multi Indicator Sustainability Assessment - Method Development and Case Studies

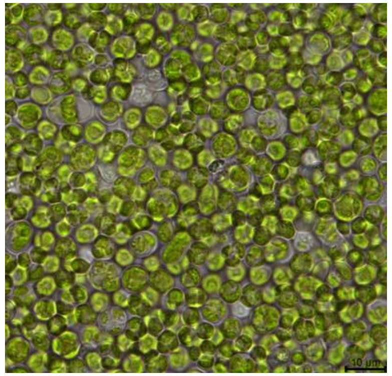
PEF based cyclic protein extraction/milking of microalgae

Contents lists available at ScienceDirect

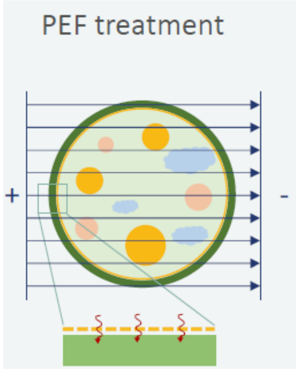
Bioresource Technology

journal homepage: www.elsevier.com/locate/biortech

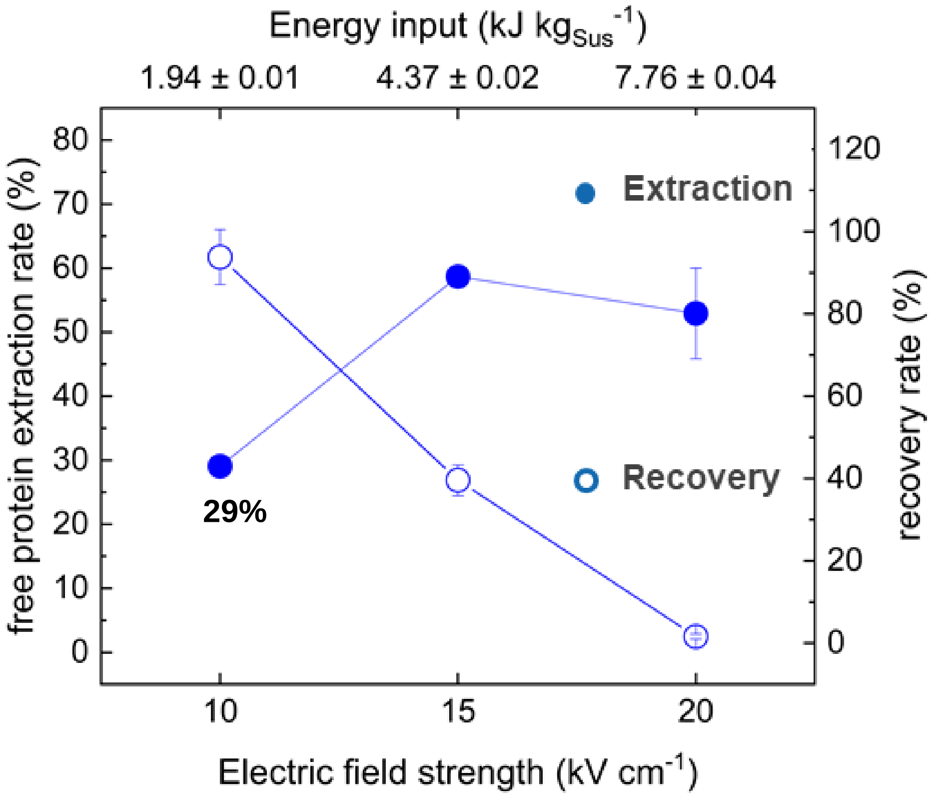
Pulsed electric field based cyclic protein extraction of microalgae towards closed-loop biorefinery concepts



(Böcker, 2021)

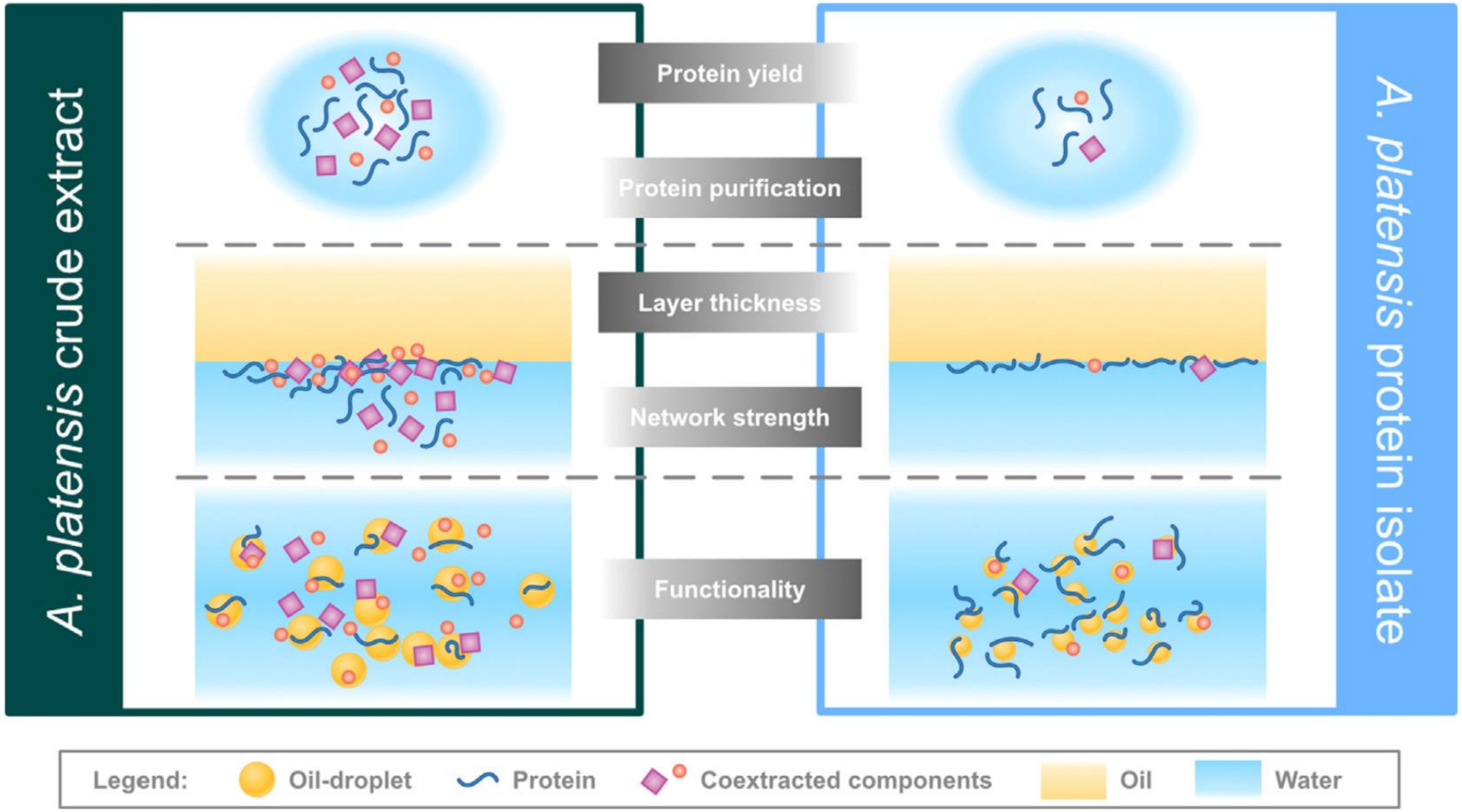


(Canelli et al, 2021)



Buchmann, Brändle, Haberkorn, Hiestand & Mathys (2019). Bioresource Technology 291,121870.

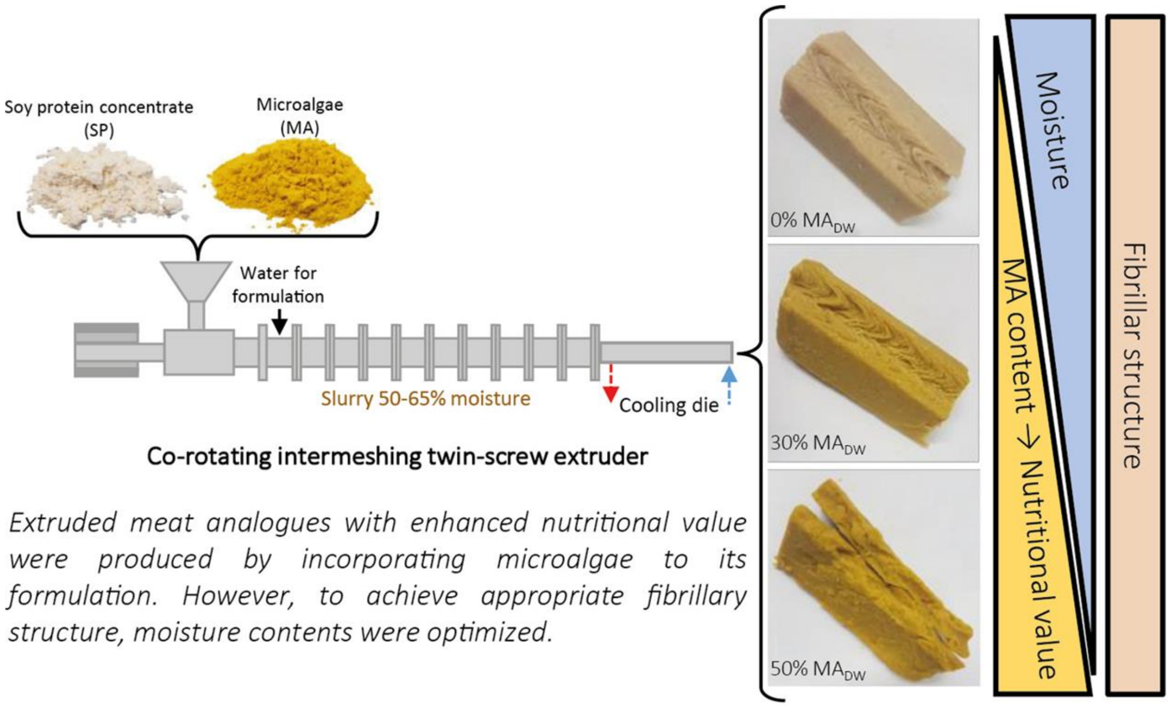
Effect of *Arthrospira* (Spirulina) protein purification on emulsification mechanism and efficiency

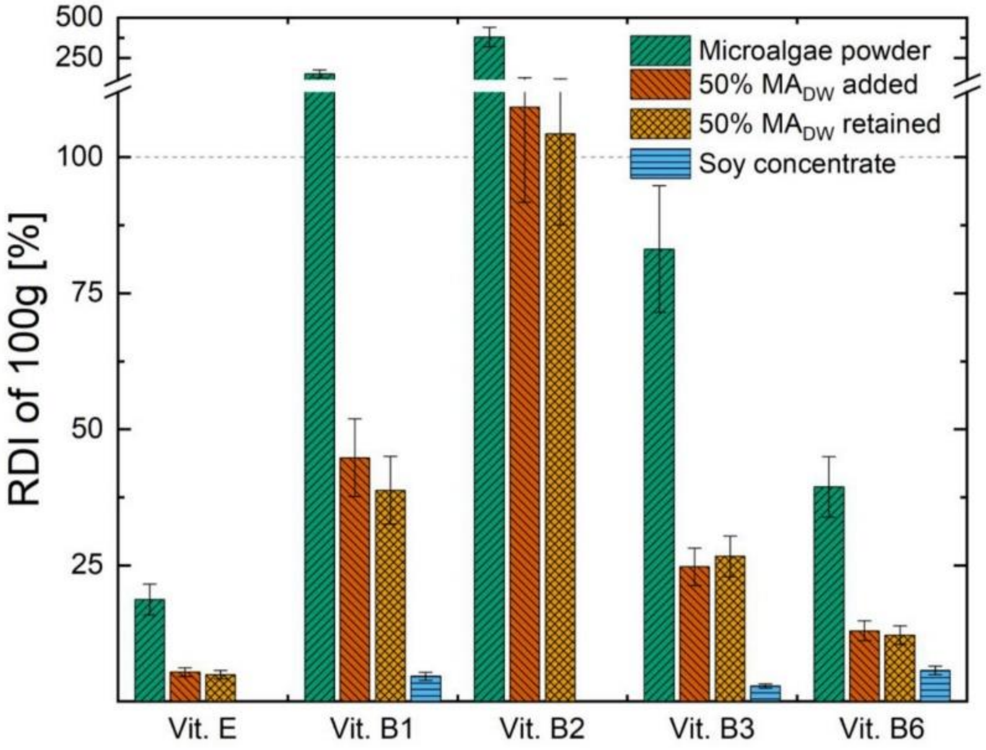


Böcker, Bertsch, Wenner, Teixeira, Bergfreund, Eder, Fischer & Mathys (2021) Journal of Colloid and Interface Science. 584, 344-353.

High moisture extrusion to produce 1st bright microalgae-based meat analogs worldwide, with increase of nutritional value

planted.





Recommended daily intake (RDI) of the selected vitamins in 100 g of unprocessed microalgae (MA) powder, extrudate with 50% MA$_{DW}$ before and after extrusion, and soy protein concentrate powder according to FDA (2016).

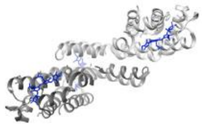
Caporgno, Böcker*, Müssner, Stirnemann, Haberkorn, Adelmann, Handschin, Windhab & Mathys (2020). Innovative Food Science and Emerging Technologies, vol. 59, pp. 102275*

ETH Sustainable Food Processing Research-Focus Microalgae

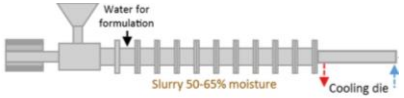
Novel Resources → Primary Production → Gentle Release → Functional Ingredients → Structure+Safety → Consumption → Biological Response

Microalgae	Algae Bioreactors	Disintegration	Proteins & Lipids	Processing	Quality Foods	Nutritive Foods

Microbial Ecosystem Analysis and Control



Structure-Process Properties Interactions



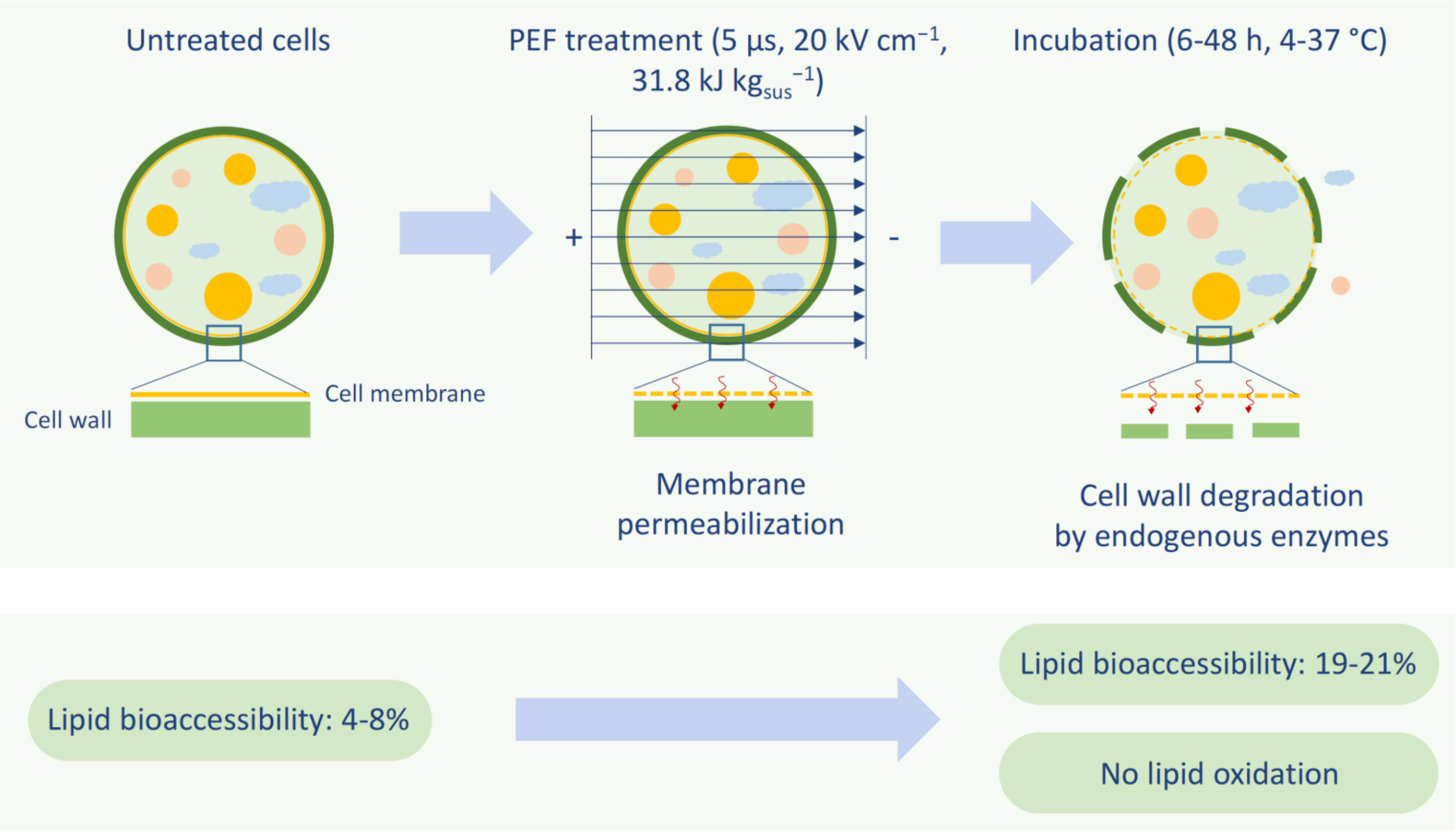
Emerging processing (Structuring/Disintegration/Safety)

Cooperation with nutrition, medicine, and consumer science

Insects	Rearing	Separation	Protein & Lipids	Processing	Quality Food/Feed	Nutritive Foods

Multi Indicator Sustainability Assessment - Method Development and Case Studies

Increased lipid bioaccessibility by pulsed electric field (PEF) and incubation

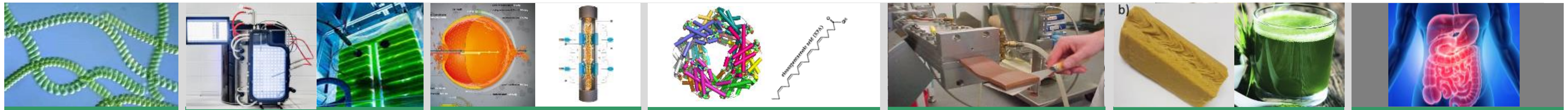


Canelli, Kuster, Jaquenod, Buchmann, Martínez, Rohfritsch, Dionisi , Bolten, Nanni and Mathys (2021). Innovative Food Science & Emerging Technologies, 75, pp. 102897

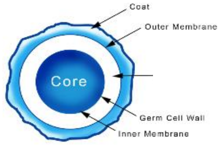
ETH Sustainable Food Processing- Summary and Future Outlook

SFP Flagship Project

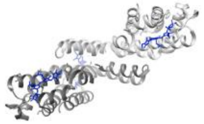
Novel Resources → Primary Production → Gentle Release → Functional Ingredients → Structure+Safety → Consumption → Biological Response



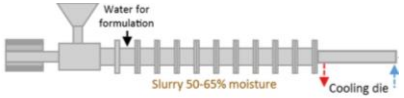
Single Cells | Bioreactors | Disintegration | Proteins & Lipids | Processing | Quality Foods | Nutritive Foods



Microbial Ecosystem Analysis and Control

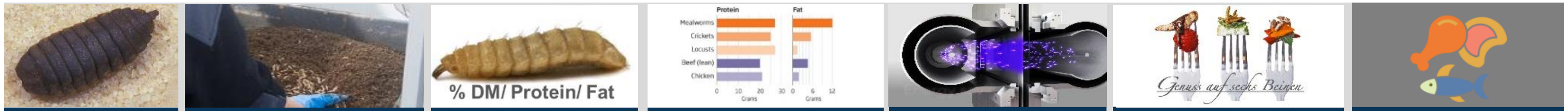


Structure-Process Properties Interactions



Emerging processing (Structuring/Disintegration/Safety)

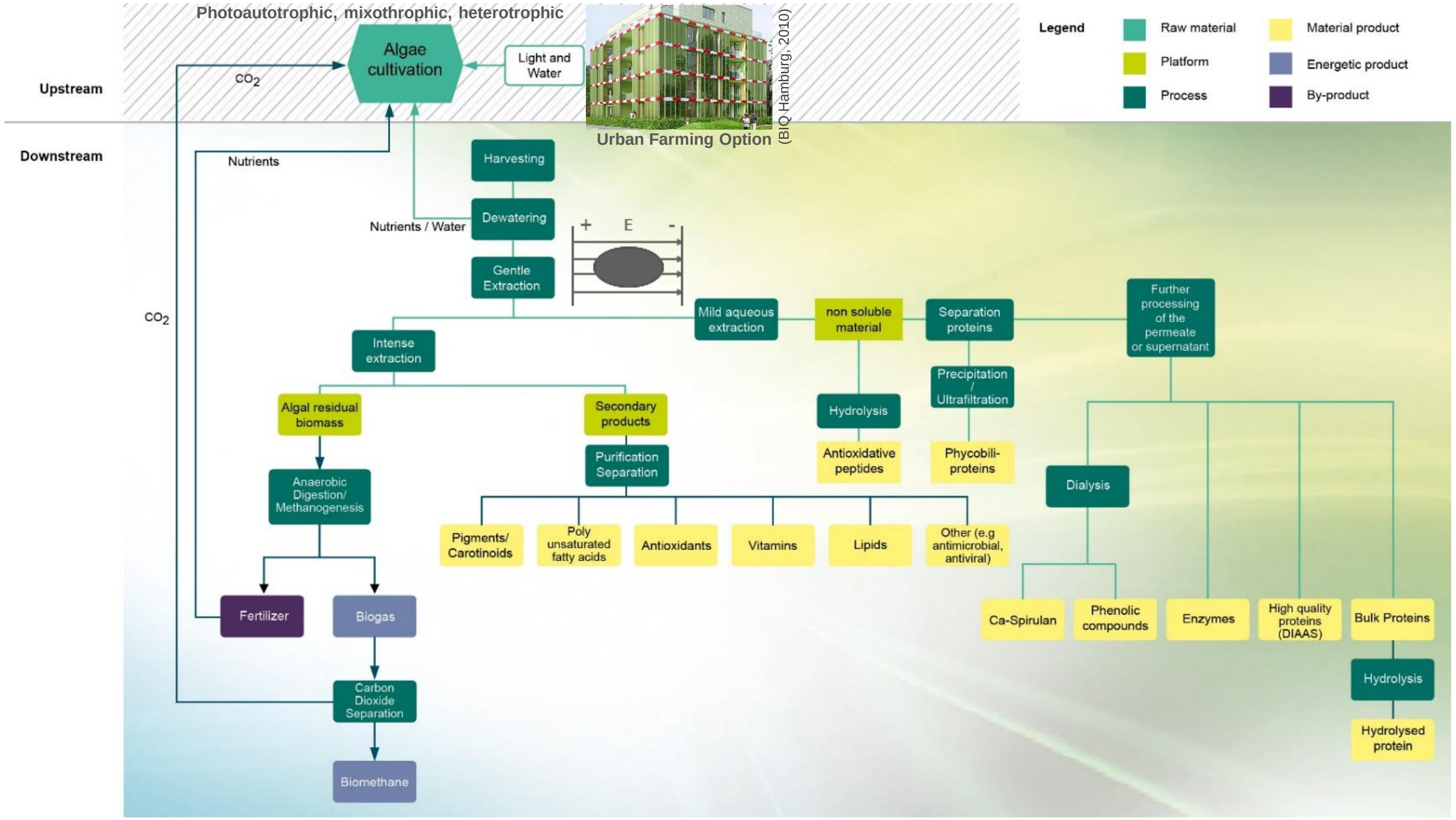
Cooperation with nutrition, medicine, and consumer science



Insects | Rearing | Separation | Protein & Lipids | Processing | Quality Food/Feed | Nutritive Food/Feed

Multi Indicator Sustainability Assessment - Method Development and Case Studies

Future outlook-How to integrate our R&D
Innovative Algae Biorefinery Concept based on emerging up- and downstream



Multi Indicator Sustainability Assessment and Connection to Nutritional R&D

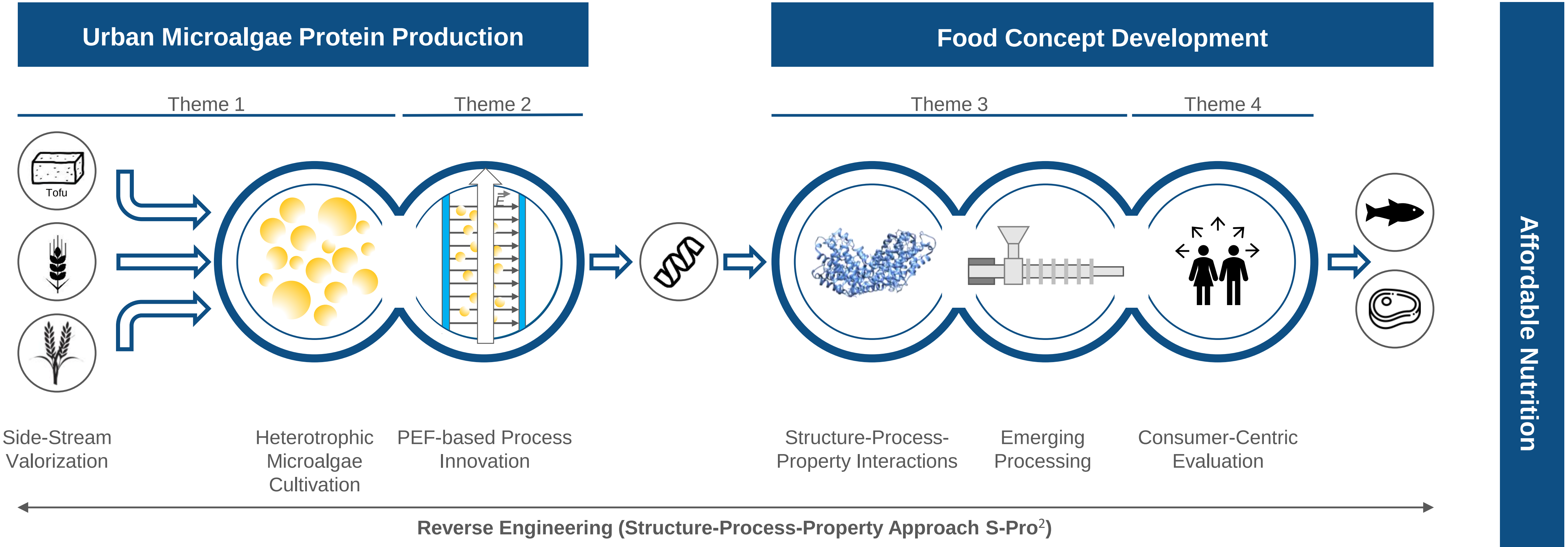
ETH zürich (SEC) SINGAPORE-ETH CENTRE World Food System Center

1) Buchmann, Bloch & Mathys, 2018
2) Buchmann, Böcker, Frey, Haberkorn, Nyffeler & Mathys, 2018
3) Caporgno & Mathys, 2018; Mathys, 2018
4) Böcker, Ortmann, Surber, Leeb, Reineke & Mathys, 2019
5) Buchmann, Bertsch, Böcker, Krähenmann, Fischer & Mathys, 2019
6) Buchmann, Brändle, Haberkorn, Hiestand & Mathys, 2019
7) Buchmann, Frey, Gusbeth, Ravaynia & Mathys, 2019
8) Buchmann & Mathys, 2019
9) Caporgno, Haberkorn, Böcker & Mathys, 2019
10) Haberkorn, Buchmann, Hiestand & Mathys, 2019
11) Smetana, Schmitt & Mathys, 2019
12) Böcker, Hostettler, Diener, Eder, Demuth, …Mathys, 2020
13) Canelli, Neutsch, Carpine, Tevere, Giuffrida, …Mathys, 2020
14) Canelli, Tarnutzer, Carpine, Neutsch, Bolten, Dionisi ...Mathys, 2020
15) Caporgno, Böcker, Müssner, Stirnemann, Haberkorn, …Mathys, 2020
16) Haberkorn, Walser, Helisch, Böcker, Belz, Schuppler …Mathys, 2020
17) Bertsch, Böcker, Mathys & Fischer, 2021
18) Böcker, Bertsch, Wenner, Teixeira, Bergfreund, Eder …Mathys, 2021
19) Canelli, Murciano Martínez, Austin, Ambühl, Dionisi, …Mathys, 2021
20) Canelli, Murciano Martínez, Maude Hauser, …Mathys, 2021
21) Haberkorn, Buchmann, Häusermann & Mathys, 2021
22) Haberkorn, Off, Besmer, Buchmann & Mathys, 2021
23) Haberkorn, Siegenthaler, Buchmann, Neutsch & Mathys, 2021
24) Canelli, Kuster, Jaquenod…Mathys, 2021
25) Canelli, Tevere, Jaquenod…Mathys, 2022
25) Canelli, Tevere, Jaquenod…Mathys, 2022
26) Canelli, Abiusi….Mathys, 2023
27) Bertsch, Böcker, Palm, Bergfreund, Fischer & Mathys, 2023

Our new lab at the Singapore ETH Center SEC
(we are looking for collaborations)

CREATE Tower. *Credit:Photography by Tim Griffith*

Urban Single-Cell Protein Production Harnessing Emerging Microalgae-based Up- and Downstream Concepts- new initiative to follow up



SOPHIE'S BIONUTRIENTS
Nestlé
BÜHLER
planted.
Givaudan
Singapore Food Agency
Safe Food For All
(SEC) SINGAPORE-ETH CENTRE
NUS National University of Singapore
Agency for Science, Technology and Research SINGAPORE

Urban Single-Cell Protein Production Team in Singapore

SOPHIE'S BIONUTRIENTS Nestlé BÜHLER planted. Givaudan Singapore Food Agency Safe Food For All

(SEC) SINGAPORE-ETH CENTRE NUS National University of Singapore Agency for Science, Technology and Research SINGAPORE

Acknowledgement

ETH zürich

DHEST
Department of Health Sciences and Technology

Whole IFNH

FNSNF
Fonds national suisse
Schweizerischer Nationalfonds
Fondo nazionale svizzero
Swiss National Science Foundation

Donors Buhler AG & Migros Industry Support

BÜHLER · MIGROS · ETH Foundation Zürich

Partners

World Food System Center · eawag aquatic research · zhaw · Wageningen University & Research · KU Leuven · University of Stuttgart Germany · NUS National University of Singapore

University of Zurich · Hes-so Haute Ecole Spécialisée de Suisse occidentale · DLR Deutsches Zentrum für Luft- und Raumfahrt · (SEC) Singapore-ETH Centre · Singapore Food Agency Safe Food For All · ETH4D · WORLD.MINDS · MaP Competence Center for Materials and Processes

Schweizerische Eidgenossenschaft
Confédération suisse
Confederazione Svizzera
Confederaziun svizra

DIL · Agroscope · scnat network swiss academy of sciences · icipe · FiBL · Agency for Science, Technology and Research Singapore · FH · Cornell Atkinson Center for Sustainability

IUFoST · IAFoST · IFT feeding the minds that feed the world · frontiers · SUSINCHAIN Sustainable Insect Chain · planted. · PROTIX · SANERGY

Nestlé · BÜHLER · MIGROS · BASF We create chemistry · Givaudan · GNT · hilcona Für Besseresser. · HAMMELMANN · EHRFELD

Thank you very much- ETH Sustainable Food Processing Lab

SUSTAINABLE FOOD PROCESSING

Prof. Dr.-Ing. Alexander Mathys
Head of Sustainable Food Processing Laboratory
alexander.mathys@hest.ethz.ch

ETH Zurich
Institute of Food, Nutrition and Health IFNH
Department of Health Science & Technology D-HEST
Schmelzbergstrasse 9
LFO E 12.2
CH-8092 Zurich
Switzerland

www.sfp.ethz.ch

alexander.mathys@hest.ethz.ch

www.sfp.ethz.ch

SUSTAINABLE **FOOD** PROCESSING

Back-up slides

Environmental sustainability of most relevant protein sources in comparison (Nutritional impacts are not included)

Environmental impact comparison of main protein sources used for feed and food (per 1 kg of product)

	DM %	Protein, %	GWP, kg CO_2 eq. global warming potential	OD, mg CFC11 ozone depletion	AC, g SO_2 eq. acidification	EU, g N eq. eutrophication	ED, MJ energy demand	FD, m^3 freshwater depletion	LU, m^2a land use
Soybean meal	87.5[1]	49.1[1]	0.34-0.72[1] 6.52[19]	0.2-0.3[1,17]	−1.2 – 3.1[1] 11.4[17]	−81-2[1] (g NO_3 eq.)	5.37[6] 25.5[19]	0.04[6]	3.26[6]
Rapeseed cake	89[1]	34.8[1]	0.37-0.57[6]	0.004-0.05[6]	6.8-7.5[6]	8.9-9.1[6]	3.3-3.8[6]	0.001-0.03[6]	1.5-1.6[6]
Pea protein meal	n/a	n/a	0.44[6] 4-10[8] (pulses)	0.057[6]	21.8[6]	7.94[6]	5.25[6]	0.03[6]	2.85[6]
Fishmeal	90[4]	60-72[5]	0.12-0.58[18] 0.65-1.8[14,3,4,13] 0.48-5.6[15,16] 5.37[17]	0.016-0.073[18] 0.83[3] 0.947-1.03[17,4]	0.12-8.7 [14,18] 7.0[13] 15.9-18.0[4,16] 56.7-62.6[19,3]	−16[4] 0.4-0.87 [3,18]	2.13-17.1[18,4,3] 21[13] 79.8[17] 120[16]	0.0002-0.0016[18] 0.0036[3] 0.347[4]	0.0005-0.0052[1,8,3] 0.6-1.1[14]
HM (this study)	96.6	56	5.3	0.43	21.3	17.9	84.18	0.0028	1.89
HP (this study)	30	17	1.16	0.091	5.3	4.6	17.9	0.0006	0.48
Fresh meat (chicken)	25-30	23-24	1.62-3.12[10]	1.8[10]	44.25[10]	75[10] (g NO_3 eq.)	18.5-65[10]	0.053-0.155[11]	19.5-31.3[11]
Whey concentrate	86-89[3]	60[3,7] 80[11,kp]	7.48[7] 0.8-7.4[6] 12.1[2] 28–43[8,kp] 40.6[11,kp]	0.01-0.06[9] 3.33[7] 3.8[11,kp]	0.05-1.5[6] 56.6[7]	1.14[6] 37.3[2] 3.59-101[9] 229.3[11,kp]	58.1[2] 83.3[7] 10.7-39.4[6]	0.003-0.066[6] 1.45[2] 9.58[7]	0.26-8.27[6]
Egg protein concentrate[9]	85	80	23.4	1.01	4000	139	183	2.65	40.1
Microalgae[9]	96	55	14.7-245.1	0.9-19.8	260.5-1407.5	40.6-105.3	217.1-4181.3	0.3-3.9	1.7-5.4

HM-Insect meal (defatted protein concentrate)
HP-Insect puree (fresh insect production)

Sources: [1] – (Dalgaard et al., 2008); [2] – (Kim et al., 2013); [3] – own calculations, [4] – Danish LCA Food Database; [5] – (Hall, 2011); [6] – ecoinvent 3 and Agrifootprint databases; [7] – (Smetana et al., 2016); [8] - (Nijdam et al., 2012); [9] – (Smetana et al., 2017); [10] – (González-García et al., 2014; Weidema et al., 2008); [11] – (Wiedemann et al., 2017); [12] – (Bacenetti et al., 2018); [13] – (Papatryphon et al., 2004); [14] – (Samuel-Fitwi et al., 2013); [15] – (Cashion et al., 2017); [16] – (Smárason et al., 2017); [17] – (Silva et al., 2017); [18] – (Fréon et al., 2017); [kp] – per kg protein. Note: HP – *H. illucens* puree (fresh insect production); HM – *H. illucens* meal (defatted protein concentrate); DM – dry mass, GWP – global warming potential; OD – ozone depletion; AC – acidification; EU – eutrophication; ED – energy demand; FD – freshwater depletion; LU – land use. CFC-11: Trichlorofluoromethane

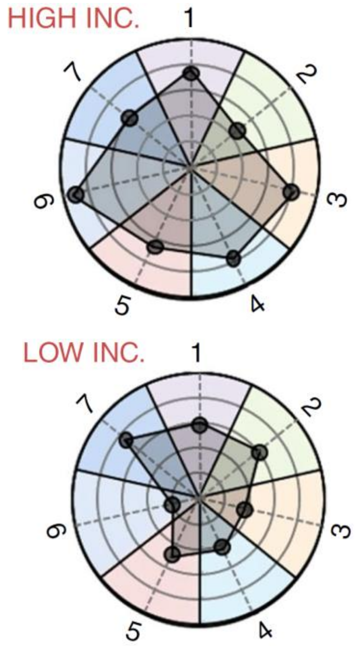
Smetana, Schmitt & Mathys (2019). Resources, Conservation & Recycling. 144, 285–296.

Multi-indicator approach quantifying the status of national food system performance

Table 1 Seven food system metrics, their indicators, and data sources

Metric		Indicator	Median	Source	GDP correlation
Food Nutrient Adequacy	1		**61**		0.53
		Shannon Diversity of Food Supply	74	Remans et al.[33]	0.42
		Non-Staple Food Energy	46	Remans et al.[33]	0.72
		Modified Functional Attribute Diversity	77	Remans et al.[33]	0.70
		Population Share with Adequate Nutrients	76	This study	0.64
		Nutrient Balance Score	75	This study	0.46
		Disqualifying Nutrient Score	12	This study	– 0.74
Ecosystem Stability	2		**47**		– 0.36
		Ecosystem Status	43	Hsu et al.[34]	0.51
		Per-Capita GHG Emissions	51	This study	– 0.79
		Per-Capita blue water consumption	50	This study	– 0.75
		Per-Capita Land Use	50	Alexander et al.[9]	– 0.09
		Per-Capita Non-Renewable Energy Use	28	World Bank[59]	0.00
		Per-Capita Biodiversity Footprint	50	Chaudhary et al.[28]	0.02
Affordability and Availability	3		**63**		0.83
		Food Affordability	54	GFSI[37]	0.85
		GFSI Food Availability Score	56	GFSI[37]	0.80
		Poverty Index	88	GFSI[37]	0.82
		Income Equality	62	World Bank[60]	0.24
Sociocultural Wellbeing	4		**60**		0.71
		Gender Equity	68	WEF[39]	0.43
		Extent of Child Labor	50	ILO[40]	0.59
		Respect for Community Rights	60	WRI[41]	0.63
		Animal Health and Welfare	60	API[42]	0.70
Resilience	5		**57**		0.64
		ND-GAIN Country Index	52	Chen et al.[43]	0.80
		Food Production Diversity	64	Remans et al.[33]	−0.20
Food Safety	6		**71**		0.76
		Global Burden of Foodborne Illnesses	50	WHO[45]	0.70
		Food Safety Score	88	GFSI[37]	0.80
Waste and Loss Reduction	7	Pre- and Post-Consumer Food Waste and Loss	**68**	FAO[46]	−0.68

Chaudhary, Gustafson & Mathys 2018, Nature Communications. 9, 848



HIC score well on most social indicators, but poorly on environmental, food waste and health sensitive nutrition indicators
→Link to our actions

Literature with partially outdated data, Microalgae standard disintegrations and their energy consumptions

Table 4. Microalgae cell disruption methods in terms of energy consumption (KWh/kg).

Technology	Microalgae species	Energy demand (KWh/kg)	References
Bead milling	*Chlorella sp, botryococcus, scenedesmus.* *Chlorella vulgaris* *Chlorella sp* *N. gaditana*	2.8–46.6 0.43–3.0 0.85 0.1–0.6	D'Hondt et al. (2017) Postma et al. (2015), Soto-Sierra, Stoykova, and Nikolov (2018) Doucha and Lívanský, (2008) Safi et al. (2017)
High pressure homogenizer	*N. gaditana* *Chlorella, tetraselmis, chlorococcum sp.*	0.32–10.44 0.25–147	Safi et al. (2017) D'Hondt et al. (2017), Grimi et al. (2014), Halim et al. (2012), Lee, Lewis, and Ashman (2012)
Ultrasound	*Chlorococcum sp, spirulina, nannochloropsis, chlamydomonas.* *Chlorococcale, Chlorophyceae* class. *Scenedesmus sp.*	0.06–36.7 1.6 0.119	Doucha and Lívanský (2008), Lee, Lewis, and Ashman (2012). Keris-Sen et al. (2014) Guldhe et al. (2014)
Pulsed electric field	*Isochrysis* *Chlorella vulgaris* *N. gaditana*	0.07 1.11 10.44	Boer et al. (2012). Postma et al. (2015) Safi et al. (2017)
Enzymatic treatment	*N. gaditana*	<0.34	Safi et al. (2017)

(Timira et al 2021)

Macronutrient composition (% per 100 g DM) of dried microalgal biomasses

TABLE 2 | Macronutrient composition (% per 100 g DM) of dried microalgal biomasses.

		Biotona	Piura	Purasana	Soleil Vie	Alver	LG-*Chlorella*
		% dry matter					
Carbohydrates	EV	11.7 ± 1.7	14.1 ± 0.7	11.0 ± 0.2	9.9 ± 0.4	20.2 ± 0.2	65.0 ± 0.3
	PV	29	17.3	22	5.2	23.5	
Proteins	EV	63.4 ± 0.0	62.7 ± 0.1	65.5 ± 0.1	64.1 ± 0.0	59.6 ± 0.0	18.9 ± 0.0
	PV	58	59.1	60	59.1	63	
Fatty acids	EV	9.8 ± 0.4	9.7 ± 0.6	9.2 ± 1.0	9.0 ± 0.6	10.0 ± 1.2	8.0 ± 0.1
	PV	12	13.4	15	13.4	11	

Experimental results are expressed as mean ± standard deviation (n = 3) and compared to reference values on the packaging's label. EV, experimental value; PV, packaging value.

Canelli, Tarnutzer, Carpine, Neutsch, Bolten, Dionisi and Mathys (2020).Front. Nutr. 7:565996.

Environmental sustainability of different microalgae protein sources in comparison (Nutritional impacts are not included)

Environmental impact comparison of main protein sources used for food and feed (per 1 kg of protein meal or powder).

	DM%	Protein,% of DM	GWP, kg CO_2 eq. global warming potential	ozone depletion OD, mg CFC11 eq.	AC, g SO_2 eq. acidification	EU, g N eq. eutrophication	ED, MJ energy demand	FD, m^3 freshwater depletion	LU, m^2a land use
Soybean meal	87.5[1]	49.1[1]	0.34–0.72 [1]	0.2–0.27[1]	−1.2 to 3.1[1]	− 81 to 2[1] (g NO_3 eq.)	5.37[6]	0.04[6]	3.26[6]
Rapeseed cake	89[1]	34.8[1]	0.37–0.57[6]	0.004–0.05[6]	6.8–7.5[6]	8.9–9.1[6]	3.3–3.8[6]	0.001–0.03[6]	1.5–1.6[6]
Pea protein meal	n/a	n/a	0.44[6] 4–10[8] (pulses)	0.057[6]	21.8[6]	7.94[6]	5.25[6]	0.03[6]	2.85[6]
Whey concentrate	86–89[3]	60[3,7]	7.48[7] 0.8–7.4[6]12.1[2]28–43[8] (kg protein)	3.33[7] 0.01–0.06[9]	56.6[7] 0.05–1.5[6]	37.3[2] 1.14[6] 3.59–101[9]	58.1[2] 83.3[7] 10.7–39.4[6]	1.45[2] 9.58[7] 0.003–0.066[6]	0.26–8.27[6]
Egg protein concentrate	85[3]	80[3]	23.4[3]	1.01[3]	4000[3]	139[3]	183[3]	2.65[3]	40.1 [3]
Fishmeal	90[4]	60–72[5]	0.884[4]	1.03[4]	18.0[4]	− 16[4]	15.8[4]	0.347[4]	n/a
Chlorella HTF[3]	96	55	14.7	0.9	260.5	40.6	217.1	0.3	4.8
Chlorella ORP[3]	96	55	245.1	19.8	1407.5	42.2	4181.3	3.3	1.9
Chlorella TBR[3]	96	55	96.1	8.9	1143.0	105.3	1516.2	3.9	5.4
Spirulina ORP[3]	96	55	196.3	15.9	1165.0	49.2	3338.3	3.2	1.7
Spirulina TBR[3]	96	55	78.1	7.2	915.9	85.3	1225.6	3.3	4.3

Sources: [1] – (Dalgaard et al., 2008); [2] – (Kim et al., 2013); [3] – own calculations, [4] – Danish LCA Food Database; [5] – (Hall, 2011); [6] – ecoinvent 3 and Agrifootprint databases; [7] – (Smetana et al., 2016); [8] – (Nijdam et al., 2012). Note: HTF – heterotrophic fermenter; ORP – open raceway pond; TBR – tubular bioreactor; DM – dry mass, GWP – global warming potential; OD – ozone depletion; AC – acidification; EU – eutrophication; ED – energy demand; FD – freshwater depletion; LU – land use. **CFC-11: Trichlorofluoromethane**

Smetana et al. 2017

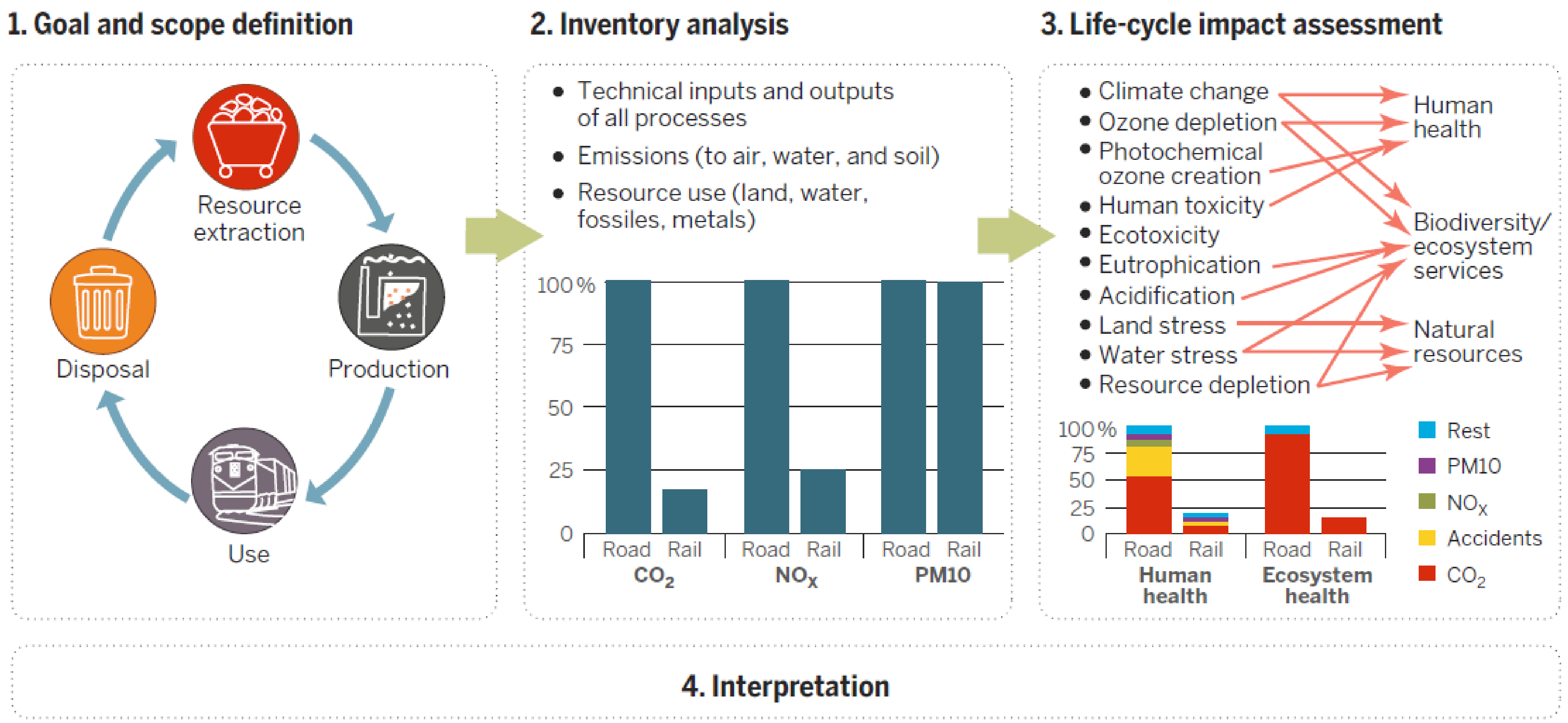
Main protein sources used for meat analogues

Protein	Protein Concentration	PDCAAS	Allergen Risk	Commercial Stage	Flavor	Functionality	Cost (/kg protein)	Global Crop Volume (MMT)
Soy	Excellent	Excellent	Poor	Excellent	Low	Excellent	Good	Excellent
Pea	Good	Good	OK	Good	OK	Good	Good	OK
Wheat	OK	OK	Poor	Excellent	OK	Excellent	Excellent	Excellent
Canola	Good	Excellent	Poor	OK	OK	Good		Good
Chickpea	Good	OK	OK	Good	OK	Good	Low	Good
Fava Bean	Good	OK	Low	OK	OK	OK	Low	OK
Lentil	Good	OK	OK	OK	OK		Low	Good
Lupin	Excellent	OK	Poor	OK	Low	OK		OK
Mung Bean	Good	OK	OK	Good	Good	Good	Low	OK
Navy Bean	Good	Good	OK	Poor	Good	OK		Low
Peanut	Good	OK	Poor	OK	Good	Good		Good
Sunflower	Good	Good	Excellent	OK	OK	Good	Low	Good
Almond	Good	Low	Low	OK	Good	OK	Low	OK
Corn	OK	Low	Excellent	OK	Good	Low	Low	Excellent
Oat	OK	Good	Good	OK	Good	Low		OK
Potato	Low	Excellent	Excellent	Good	OK	Good	Low	Excellent
Quinoa	OK	Good	Good	Poor	OK	Good	Low	Low
Rice	Low	OK	Excellent	Good	Good	OK	OK	Excellent
Sorghum	Low	Low	Excellent	Poor	Good	Poor		Good

	Protein Concentration	PDCAAS	Allergen Risk	Commercial Stage	Flavor	Functionality	Cost (/kg protein)	Global Crop Volume (MMT)
Excellent	>30%	>0.8	Usually mild, low pop.	Commodity	Flavorless	Low conc. effect	<$2	>100
Good	20-30%	0.6-0.79	↕	Large	↕	↕	$2-4	10-99
OK	10-20%	0.40-0.59	↕	Small	Acceptable	↕	$5-9	1-9
Low	5-10%	0.20-0.39	↕	Start-up	↕	↕	$10-19	0.1-0.9
Poor	<5%	<0.20	Severe in sig. pop.	R&D	Objectionable	Water insoluble	>$20	<0.1

https://gfi.org/resource/plant-protein-primer/

Environmental Life Cycle Assessment LCA Framework with example



(Hellweg & Canals, 2014)