

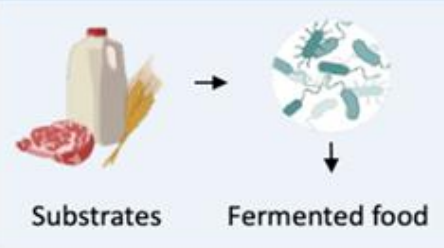
Microbial foods: Fermentation challenges and opportunities

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Microbial foods

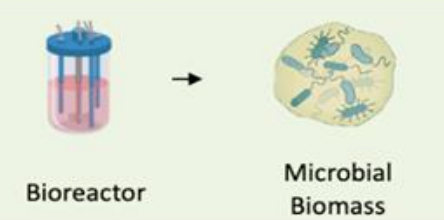
Traditional fermentation



Fermented foods (cheese, bread, Kimchi, sauerkraut, beer)

Starter cultures (lactic acid bacteria, *Bacillus*, yeasts, fungi)

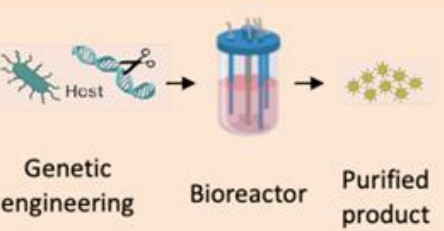
Biomass fermentation



Microbial protein- Mycoprotein

Single cell cultures (yeasts, bacteria)

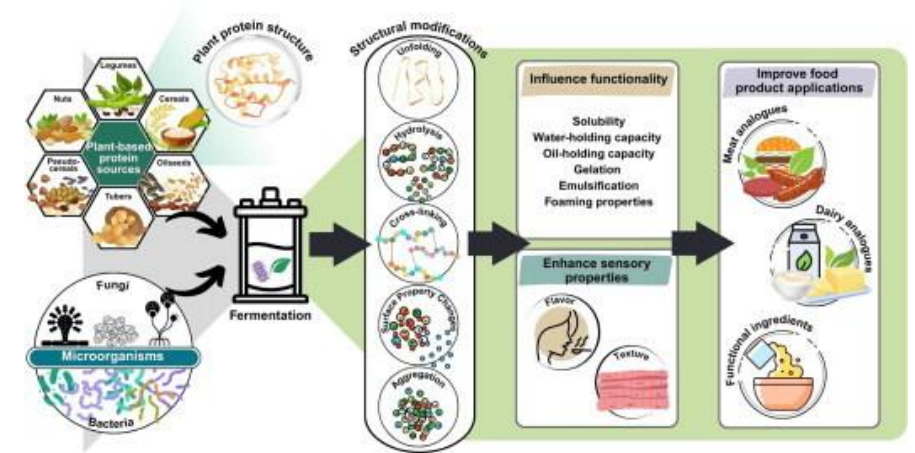
Precision fermentation



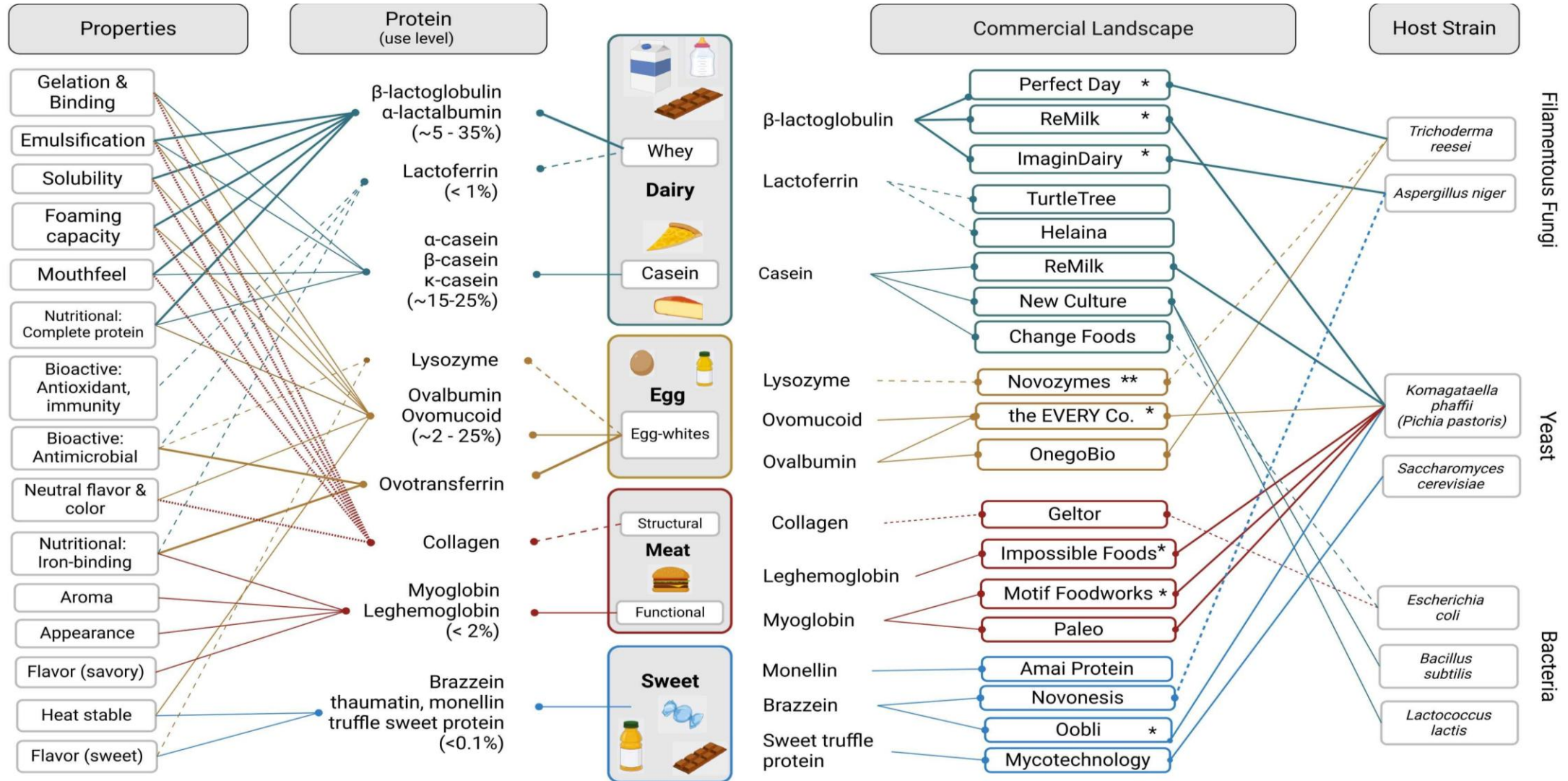
Food ingredients (lactoferrin, egg-whites, lipids, vitamins)

Single cell cultures – Genetically engineered strains (yeasts, bacteria, fungi)

Modification of plant materials by fermentation

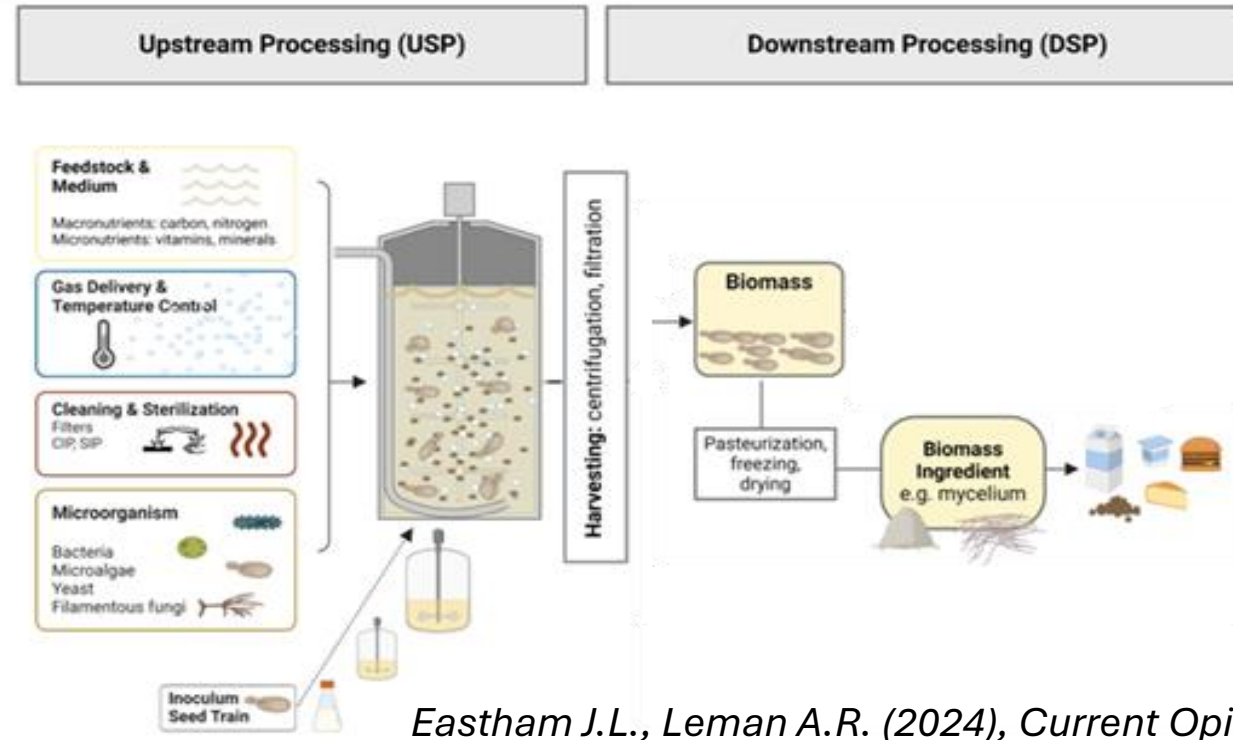


Precision fermentation derived proteins



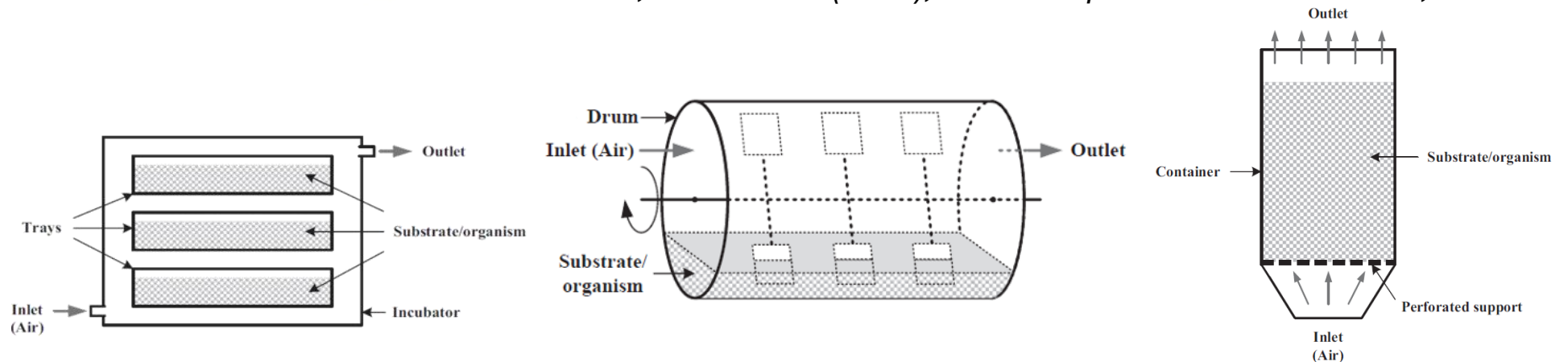
Microbial biomass production

Submerged fermentation

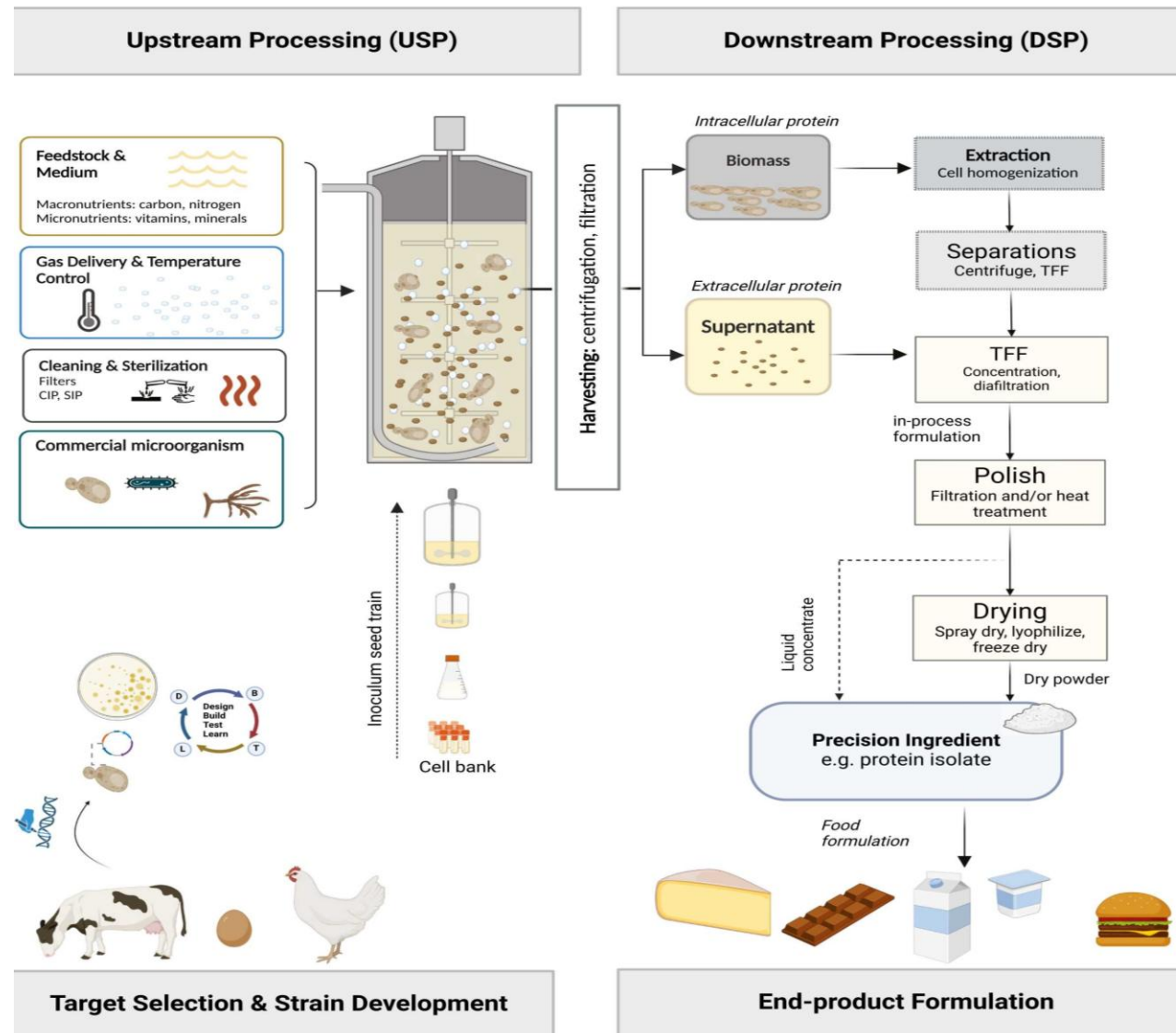


Eastham J.L., Leman A.R. (2024), *Current Opinion in Food Science*, 58:101194

Solid-state fermentation (SSF)

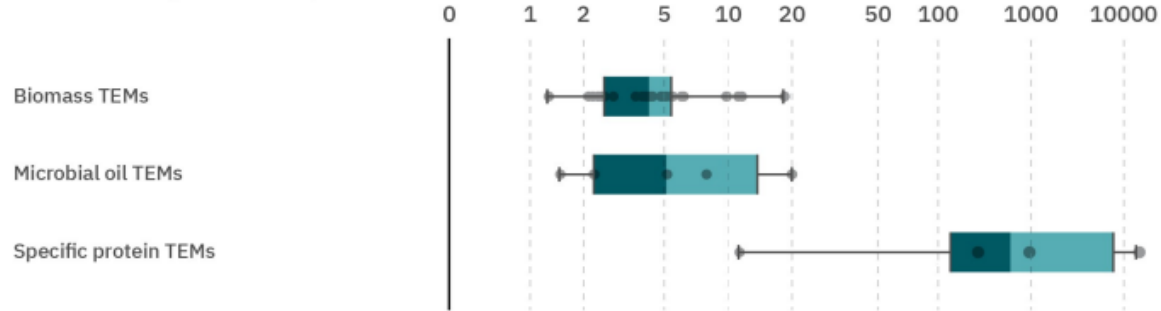


Precision fermentation proteins production

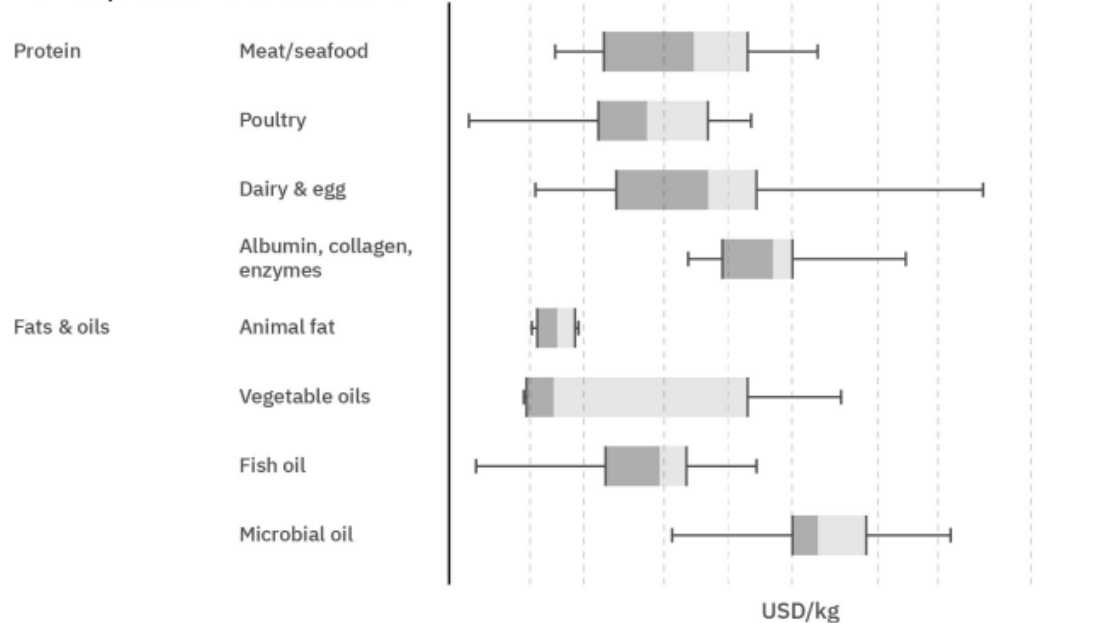


Cost of production for biomass – Technoeconomic models (TEM)

TEM landscape: Cost of production

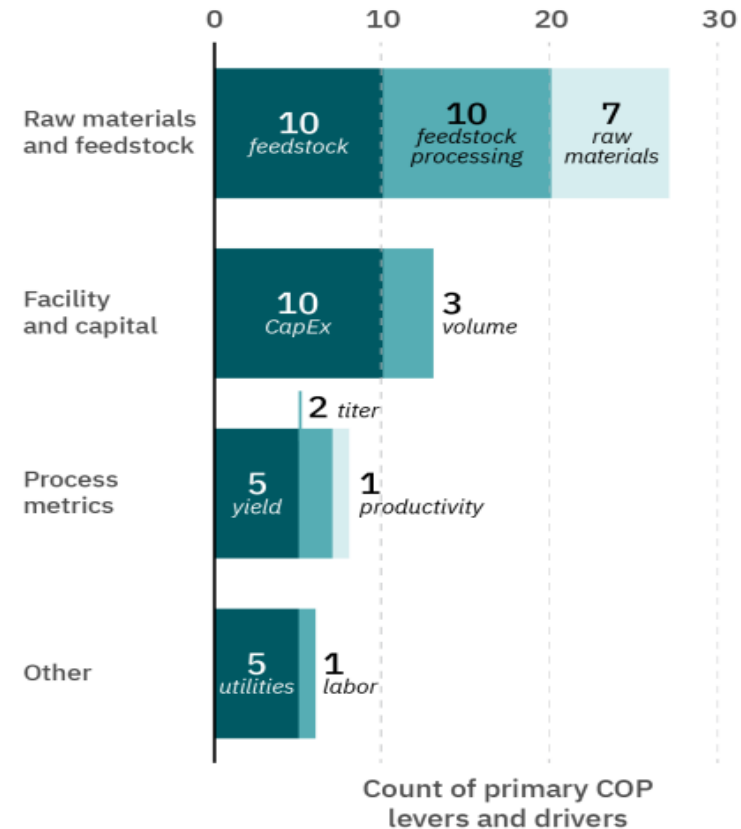


Market prices: Proteins and oils



Limited TEM studies on PF proteins

Cost of production driver overview



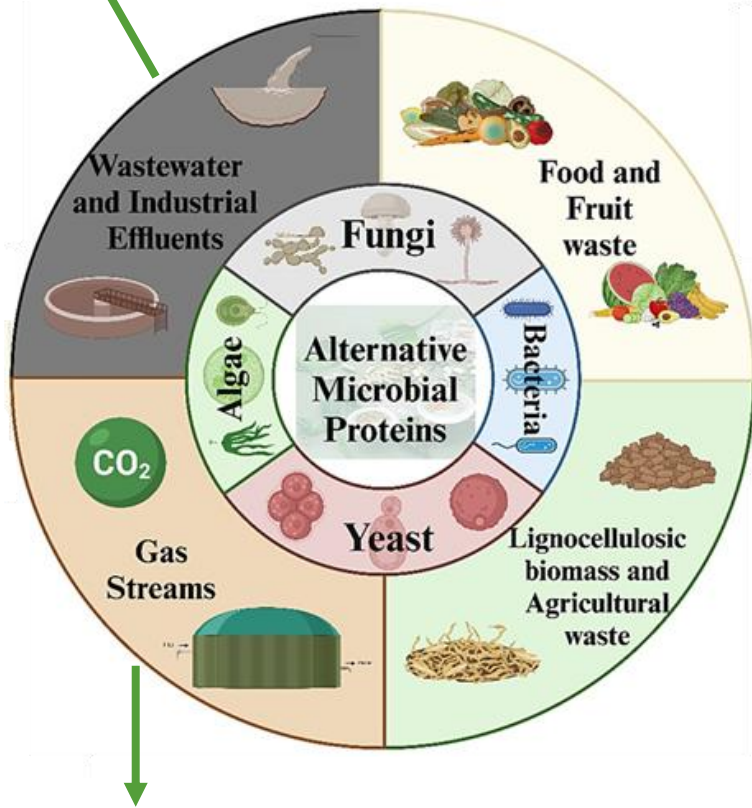
Key fermentation challenges

- ↓ Cost of production (COP)
- ↑ Process optimisation & performance [e.g. microbial biomass yield, concentration (~80-120 DCW/L and productivity)]
- Process scalability (from lab → production) – **maintain** process performance
- **Control** the impact of fermentation on protein quality (e.g. texture, flavour, nutritional value)

Feedstocks

1st Generation feedstock: sugar (glucose)

Feed applications



2nd generation feedstock
Food/feed applications

3rd Generation feedstock

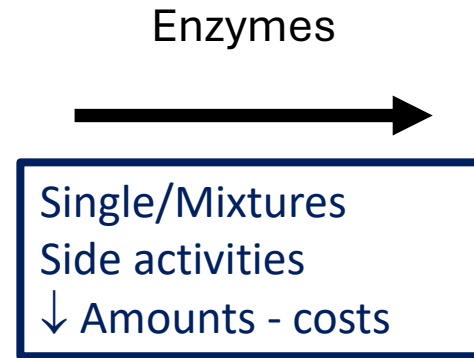
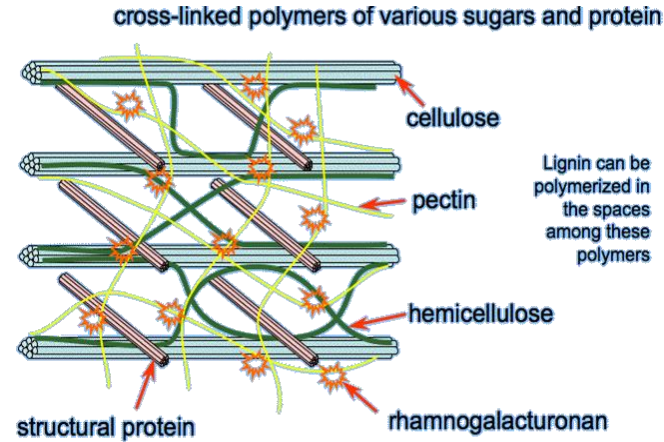
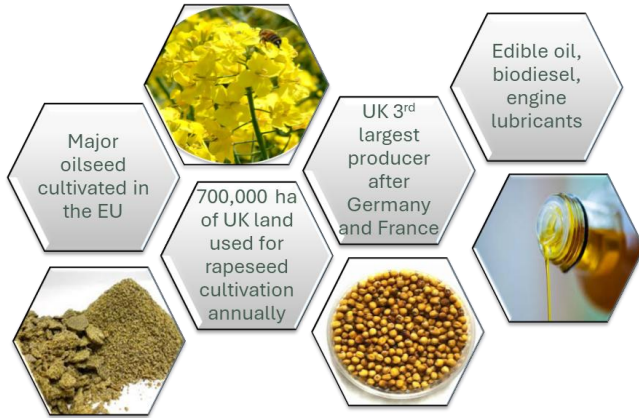
Wankhede, L. et al. (2025) *Systems Microbiology and Biomanufacturing*, 5, 1–14



Nadar, C.G. et al. (2024) *Comprehensive Reviews in Food Science and Food Safety*, 23:e13375

Raw materials	Microbial group
Lignocellulosic biomass and agriculture waste 	
Food and Fruit Waste 	
Wastewater and industrial effluent 	
Gas streams 	

Rapeseed meal as feedstock for red-pigmented yeast biomass production



- Glucose
- Xylose
- Fructose
- Arabinose
- Galactose
- Uronic acids

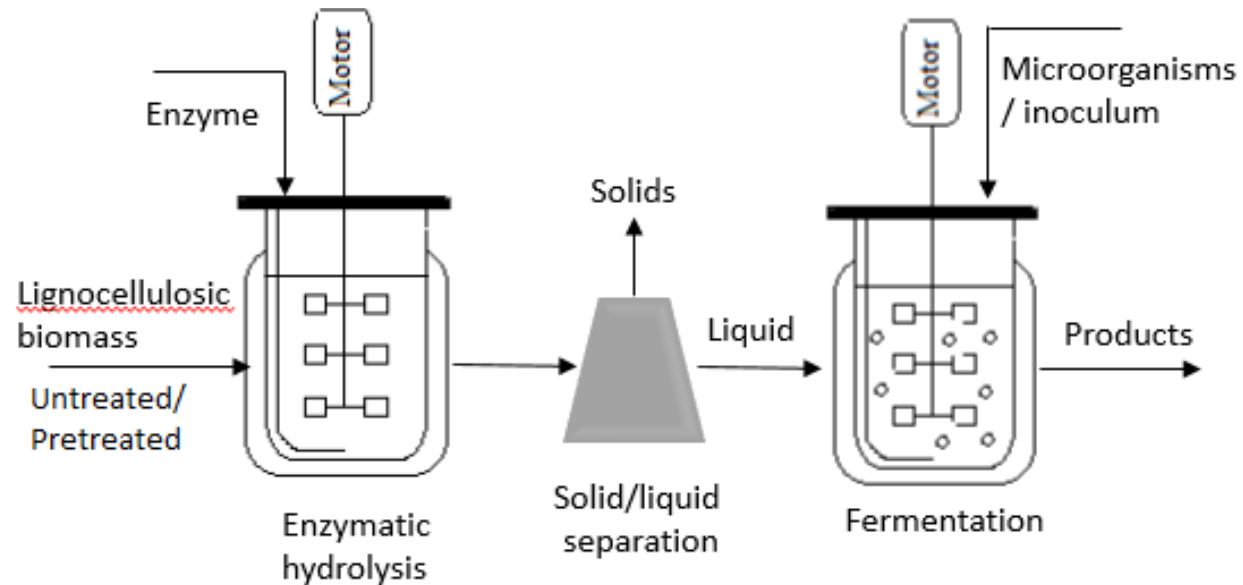
Utilisation by cells?

Flask cultures

RSM hydrolysate	Time (h)	Biomass (g/l)	Astaxanthin (mg/l)	EtOH _{max} (g/l)
Viscozyme L	115	3.1 ± 0.1	0.4 ± 0.1	3.8 ± 0.1
Cellulase	115	14.6 ± 0.6	1.1 ± 0.2	6.9 ± 0.1
Pectinase	120	25.8 ± 1.5	6.7 ± 0.4	-
Accellerase	118	8.2 ± 0.1	2.7 ± 0.1	2.0 ± 0.2

2-L Batch bioreactor fermentations with rapeseed meal hydrolysates

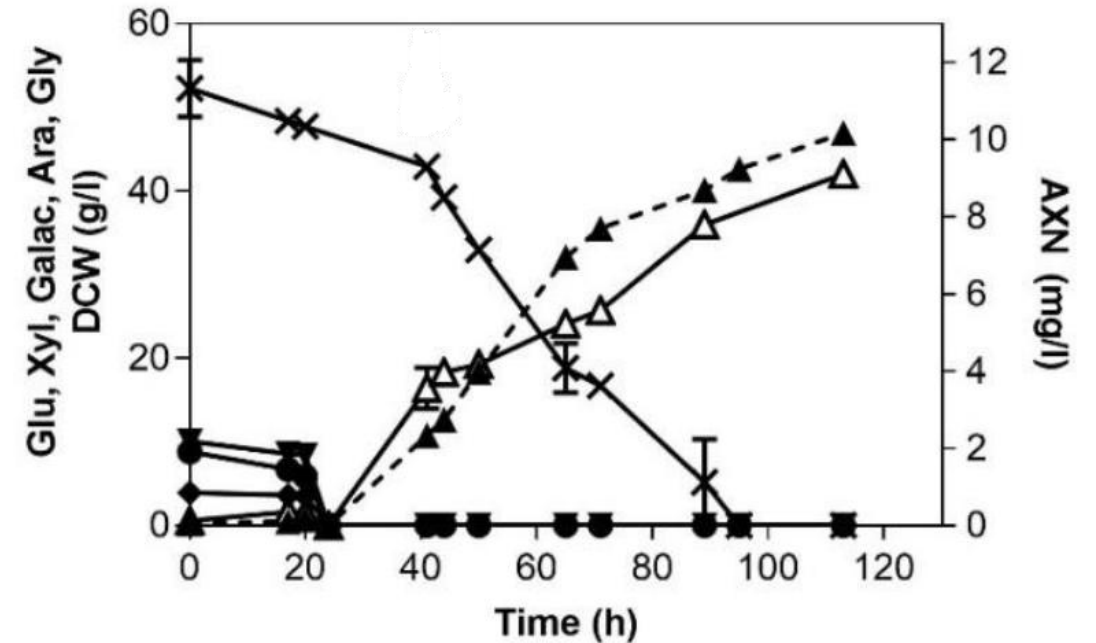
Separate hydrolysis and fermentation



2-L Batch bioreactor fermentations with rapeseed meal hydrolysates

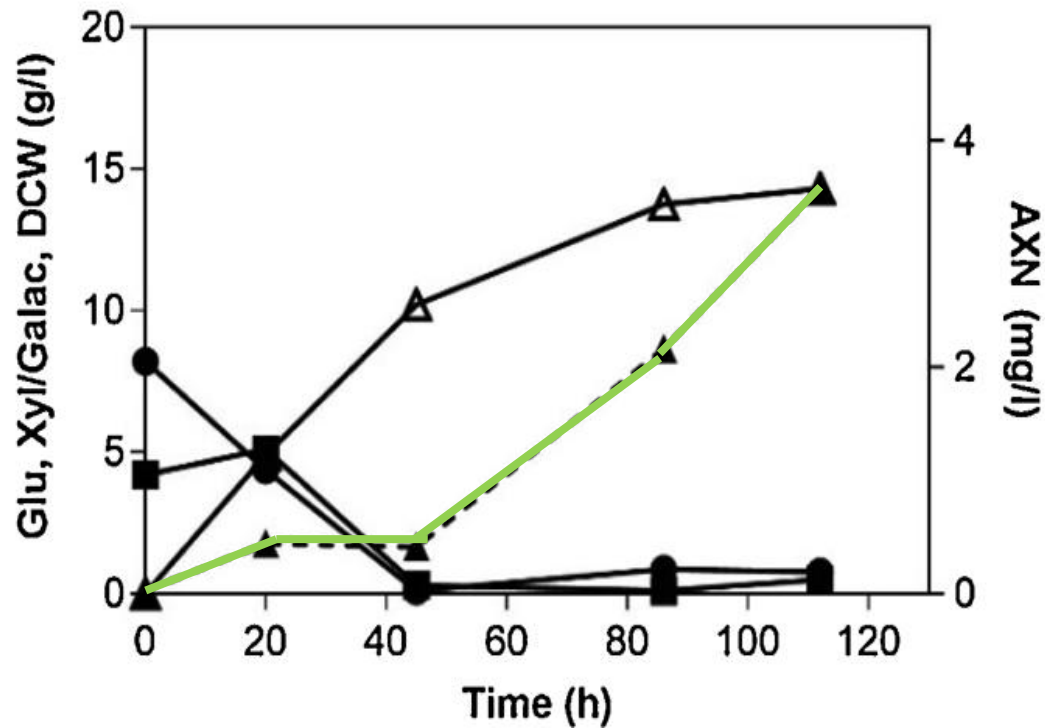
RSM hydrolysate	Time (h)	Biomass (g/l)	Astaxanthin (mg/l)
Cellulase	120	25.3 ± 0.3	7.6 ± 0.1
Pectinase	120	39.8 ± 0.1	10.8 ± 0.2
Accellerase	112	14.3 ± 0.9	3.6 ± 0.1

Glu (●); Xyl/Galac (▼), Ara (◆); Gly (×); DCW (Δ); AXN (▲)

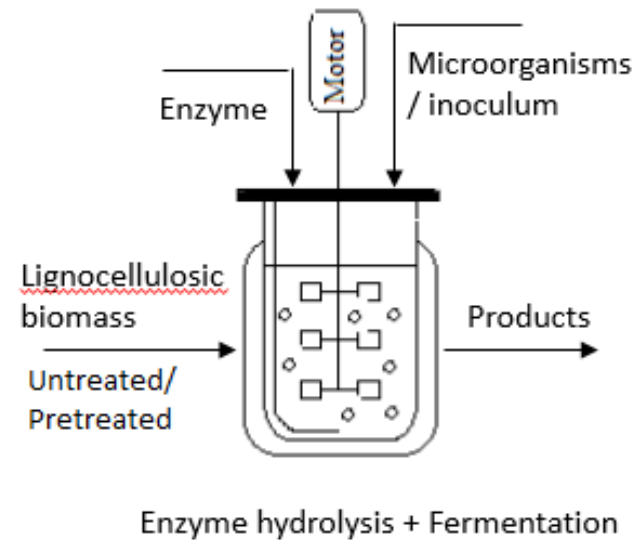


2-L Batch bioreactor fermentations with rapeseed meal hydrolysates

Separate hydrolysis and fermentation

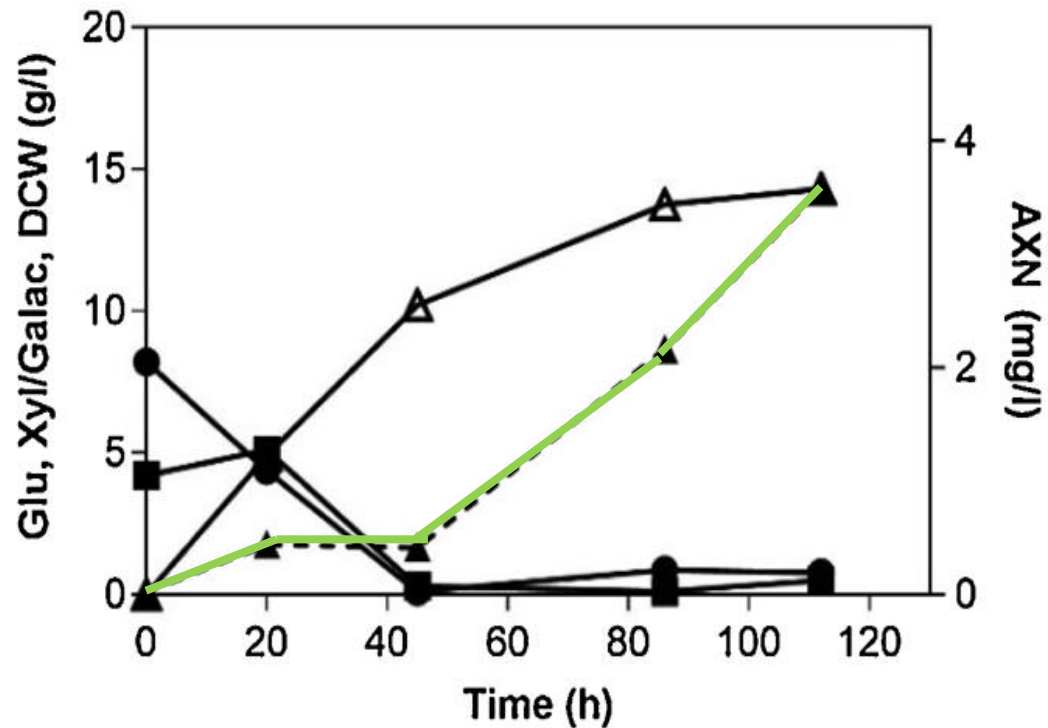


Pre-hydrolysis and fermentation in one vessel

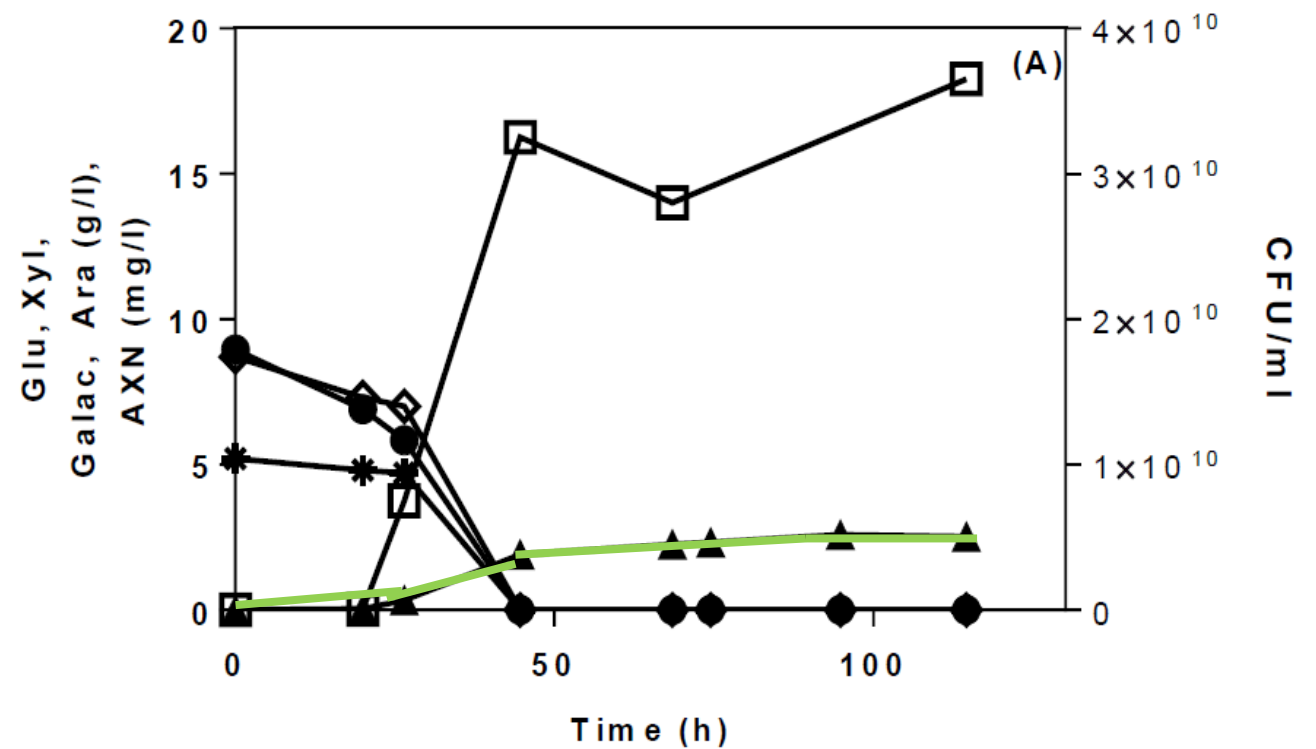


2-L Batch bioreactor fermentations with rapeseed meal hydrolysates

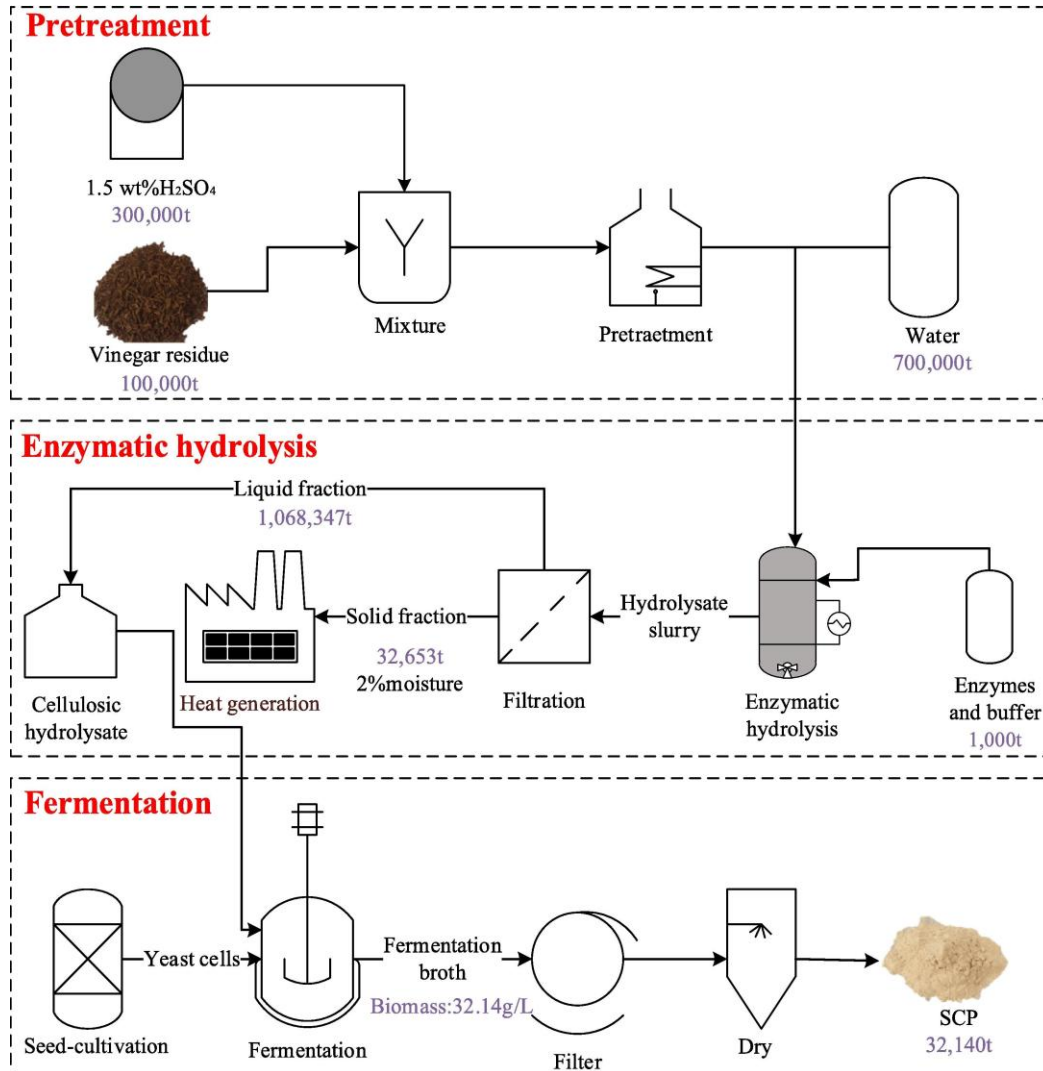
Separate hydrolysis and fermentation



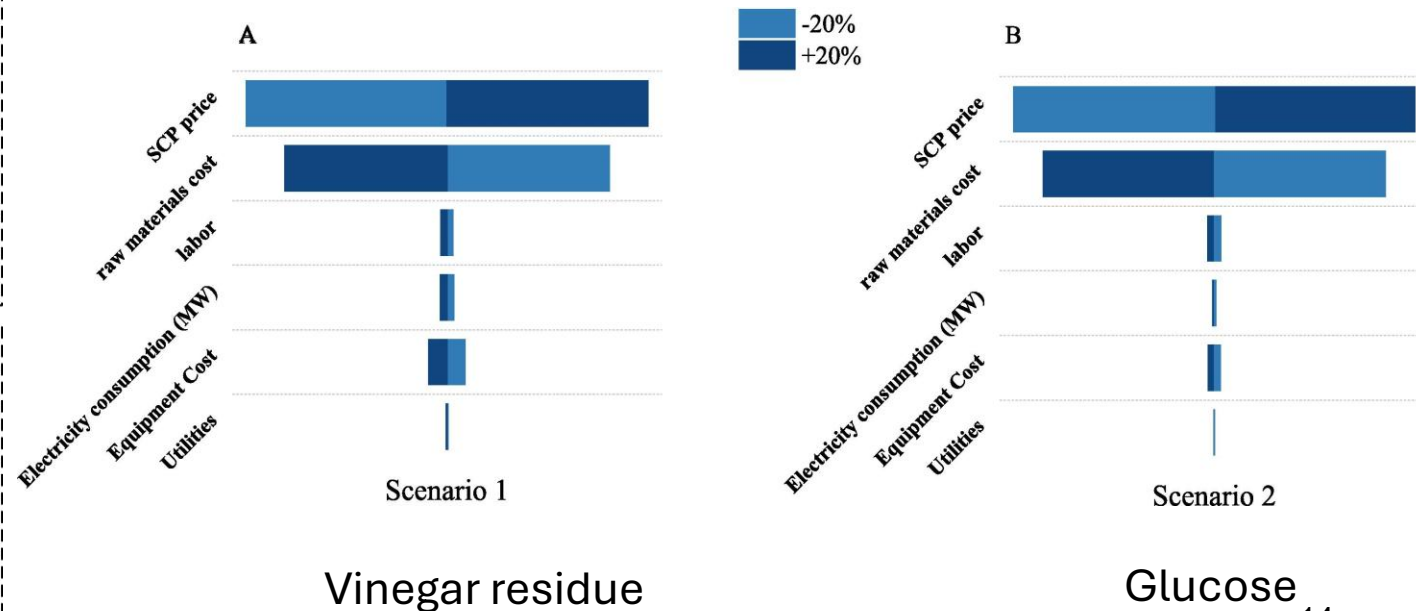
Pre-hydrolysis and fermentation in one vessel



Production of yeast single cell protein from vinegar residue

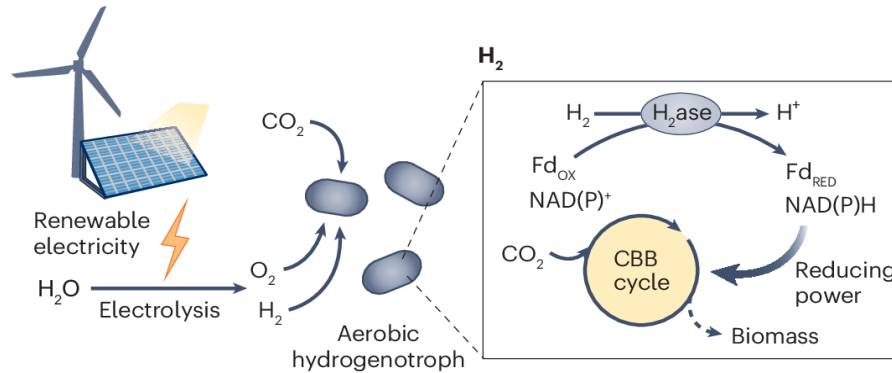
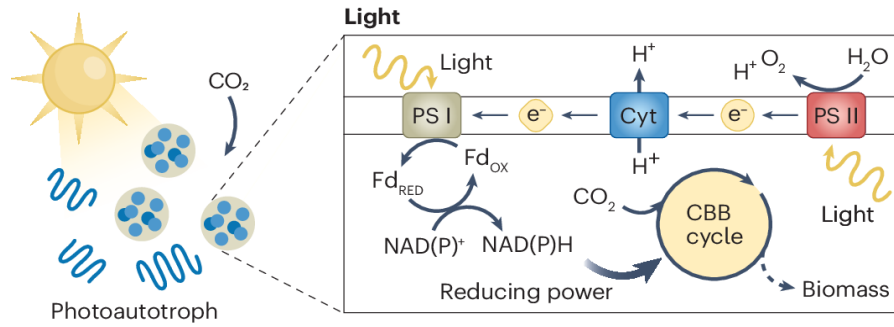


Sensitivity analysis of economic process performance

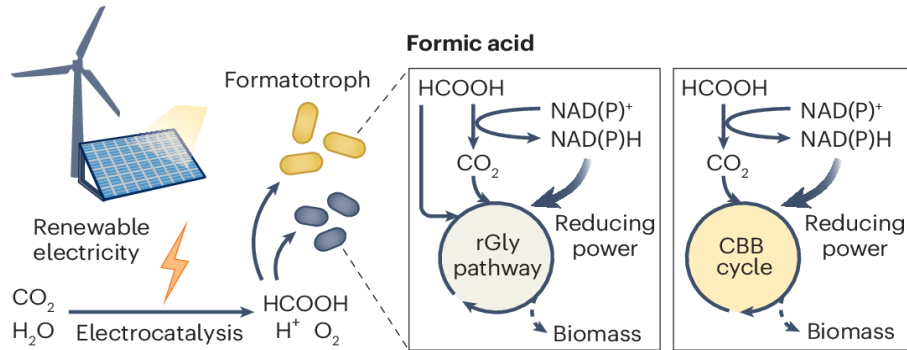


C-1 feedstocks

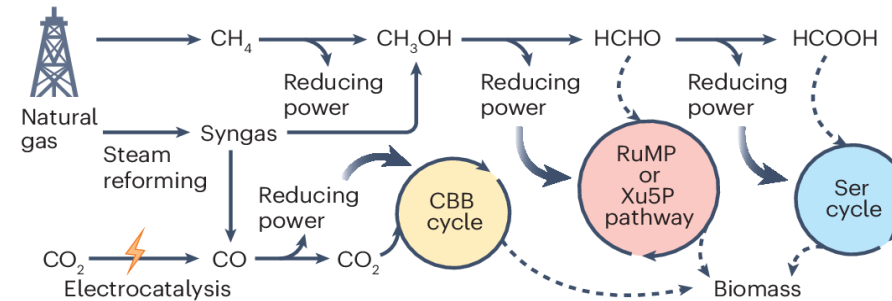
Direct utilization of CO₂



Indirect utilization of CO₂



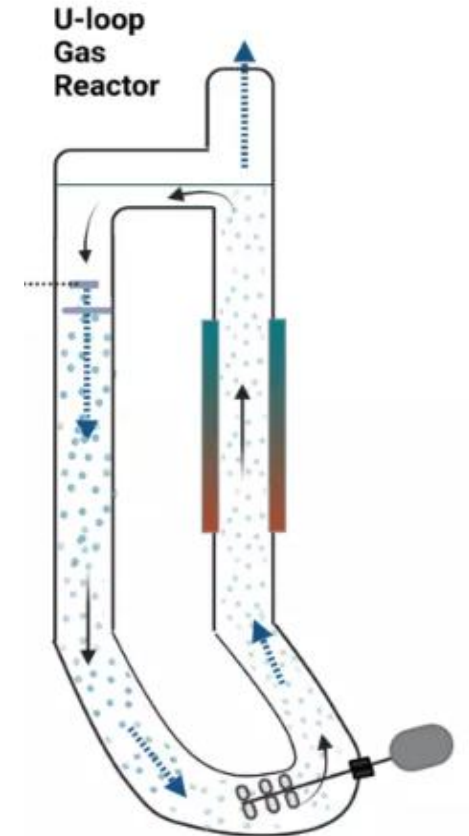
Other C1 compounds



Choi, K. R. et al. (2024), Nature Microbiology, 9, 1167–1175

Challenges

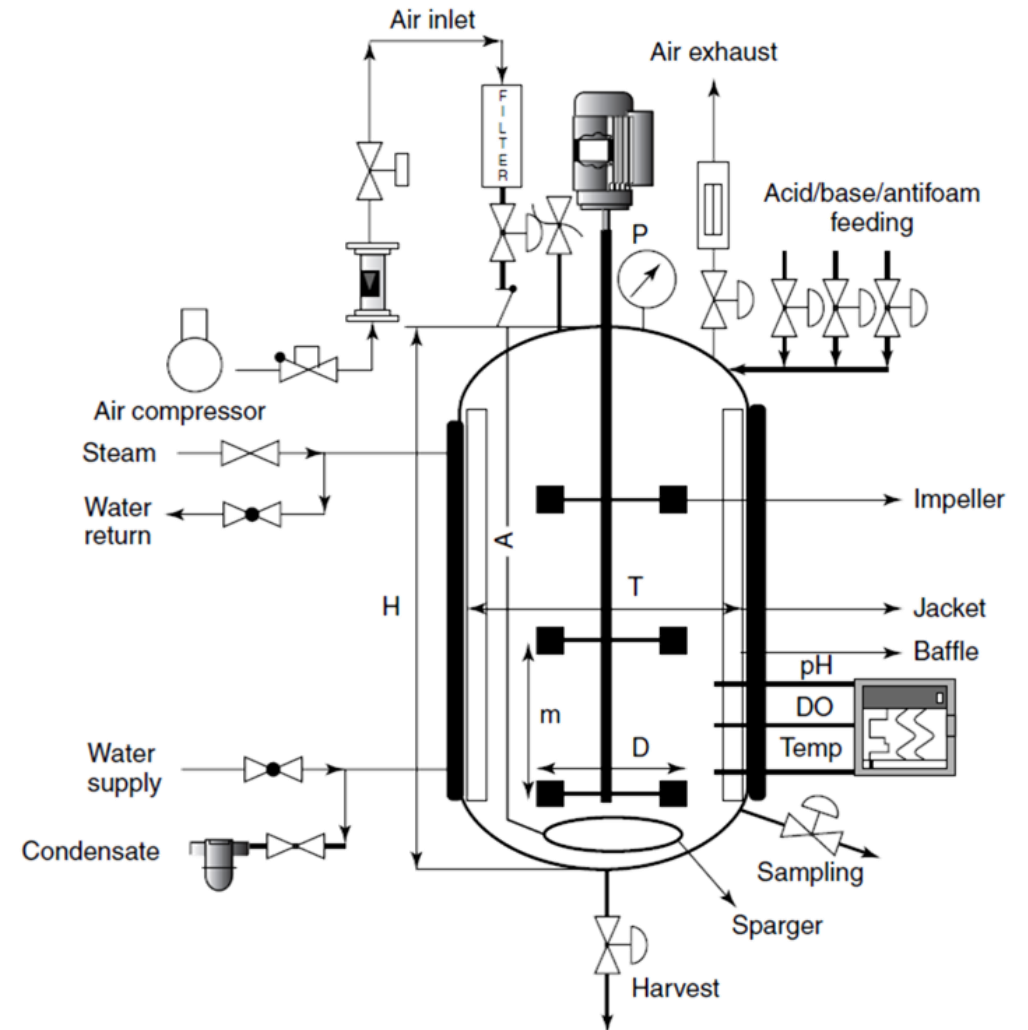
Solve Metabolic and Energetic Bottlenecks
 Bioreactor design - ↑ Gas-Liquid Mass Transfer
 Process Safety



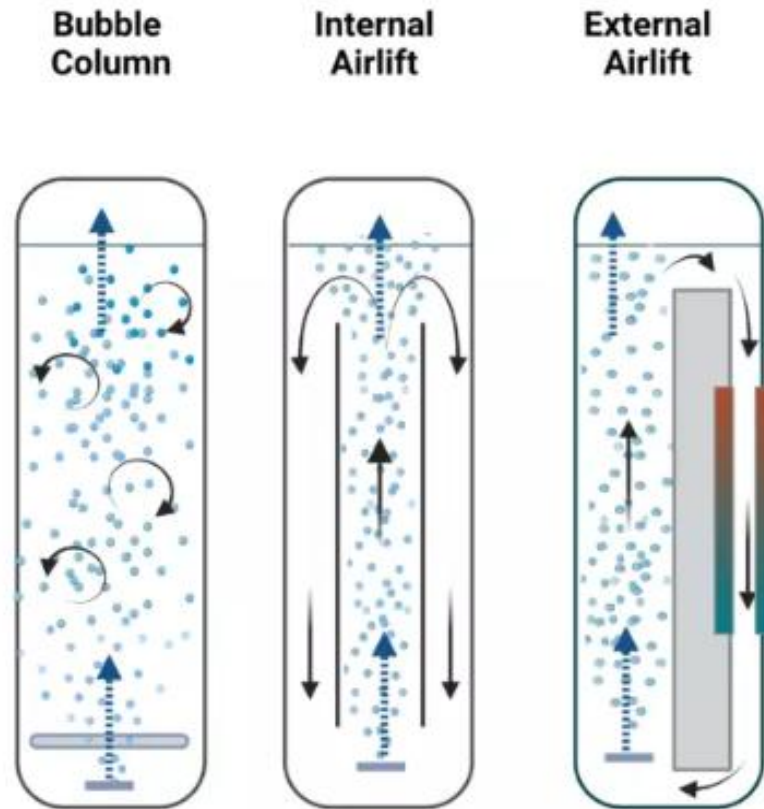
Bioreactor design, fermentation operation & process scalability

Stirred Tank Bioreactor

- Aerobic fermentations
- High cell density \uparrow oxygen demand
- Mass transfer coefficients (kLa) become critical engineering parameters - High oxygen transfer rates \rightarrow High biomass productivity
- Mixing gradients create uneven nutrient and pH conditions
- Foaming and heat removal become major operational concerns



Pneumatic bioreactors

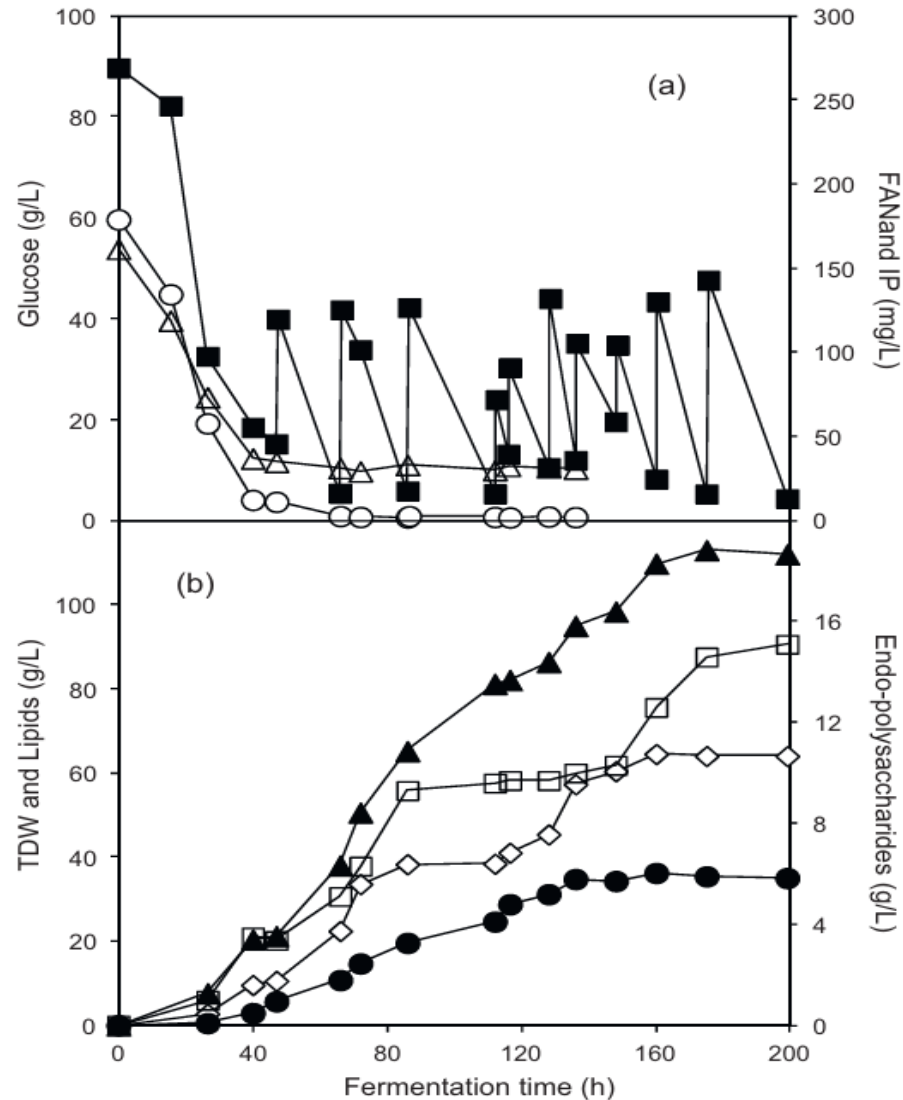


Advantages

- Effective Mass Transfer
- Low Shear Stress
- Simple designs – low capital costs
- High Energy Efficiency – low operation costs
- Easy Sterilisation

Extensively used for mycoprotein production
Limited R&D in bacterial and yeast fermentations

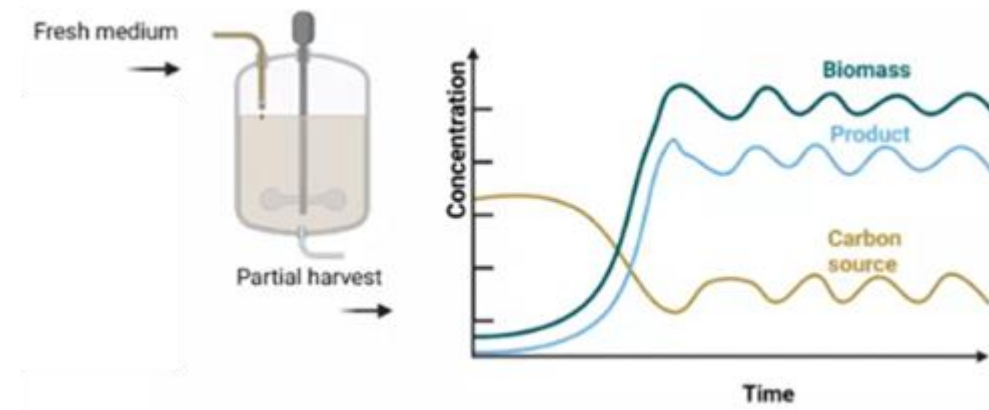
Achieving high cell densities - Fed-batch cultivation



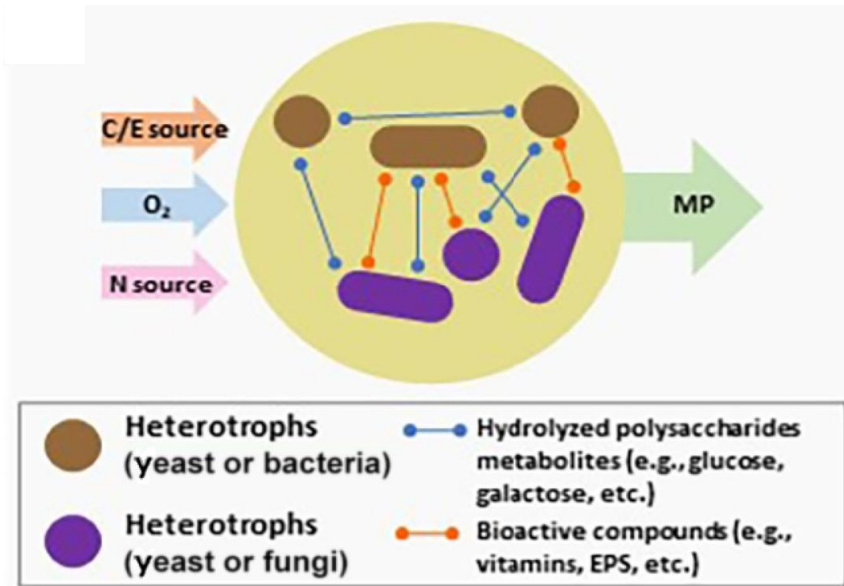
Advantages

- Higher biomass yield and density
- Prevention of substrate inhibition
- Control over oxygen transfer
- Improved product quality and consistency

Continuous bioreactor?

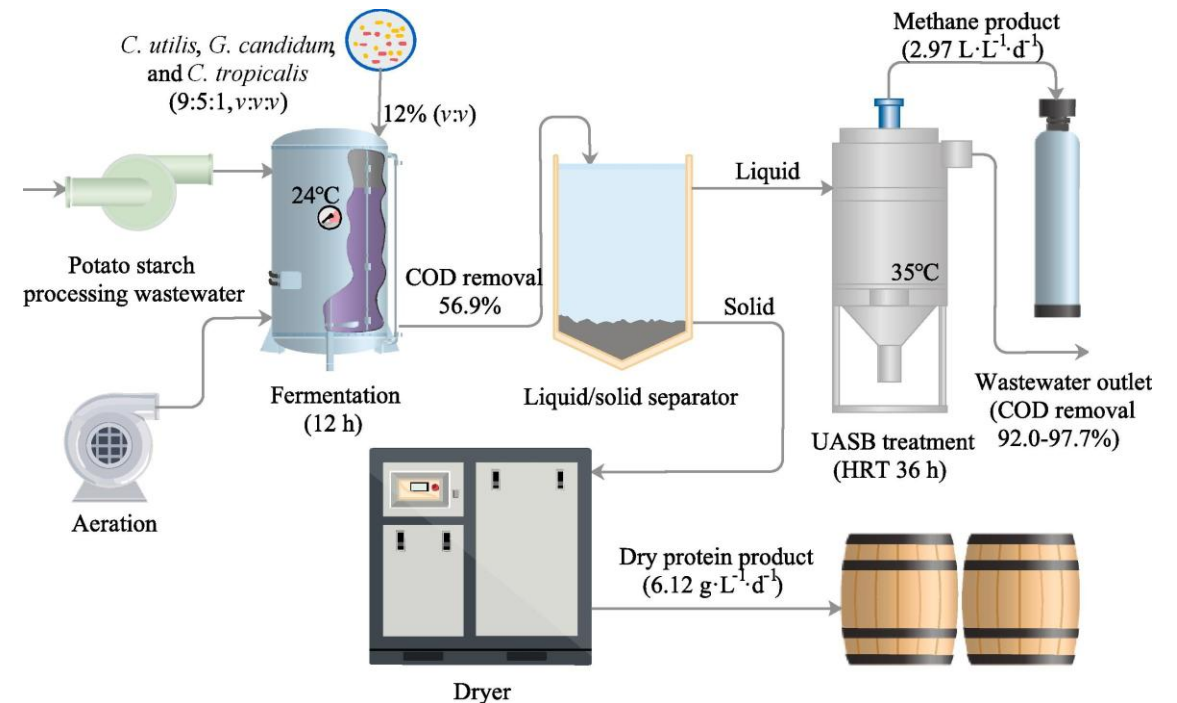


Co-culture for higher biomass yield and productivity



Areniello, L. et al. (2023), *Trends in Biotechnology*, 41, 2

- Cross-feeding
- Enzyme synergies
- Removal of inhibitory components
- Shorter fermentation times



Tian, Y. et al. (2023), *Bioresource Technology*, 128527

Key scale up parameters

Parameter	Deviation	Impact
Feedstock quality	Grade (industrial vs reagent), purity, concentration, variability	Impurities and unfermentable components can impact titer, rate and yield
Feedstock and medium sterilization	Batch vs continuous sterilization (lab vs commercial)	Sterilization mode may impact the stability or degradation of medium components
Mixing	Increased mixing time or decreased homogeneity	Lower productivity due to gradients that may form for parameters like temperature, pH, DO, and substrate
Gas-liquid volumetric mass transfer	Changes in the gas distribution or mixing due to equipment and cost limitations	Slower or unequal gas distribution leads to lower productivity
Liquid hydrostatic pressure	Large vessel increases pressure gradient	Increased gas concentrations impact productivity and cell stress
Shear stress	Increased shear in some conditions to maintain mixing	High shear stress affects cell morphology, productivity, or DSP yield

Innovation needs

Cheap feedstocks and process optimisation

Co-cultures and Continuous fermentation systems

Understanding impact of fermentation on texture, colour, flavour, digestibility, nutrition



Engineering principles for bioreactor design and scale up

AI-driven strain optimisation and digital bioprocessing

Precision control of fermentations using sensors and automation

Integration with renewable energy and circular bioeconomy systems

Thank you!