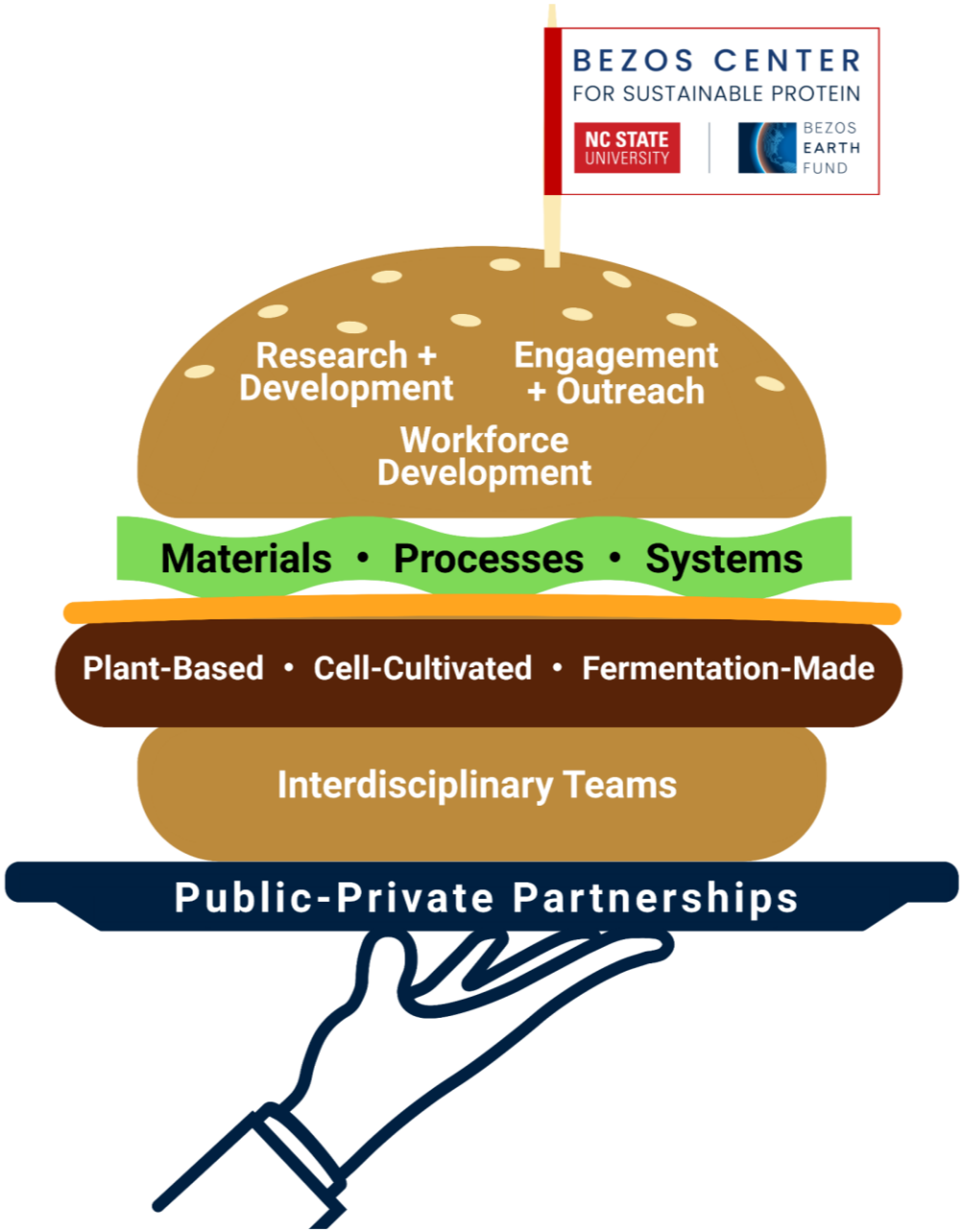


BRIDGE2FOOD EUROPE

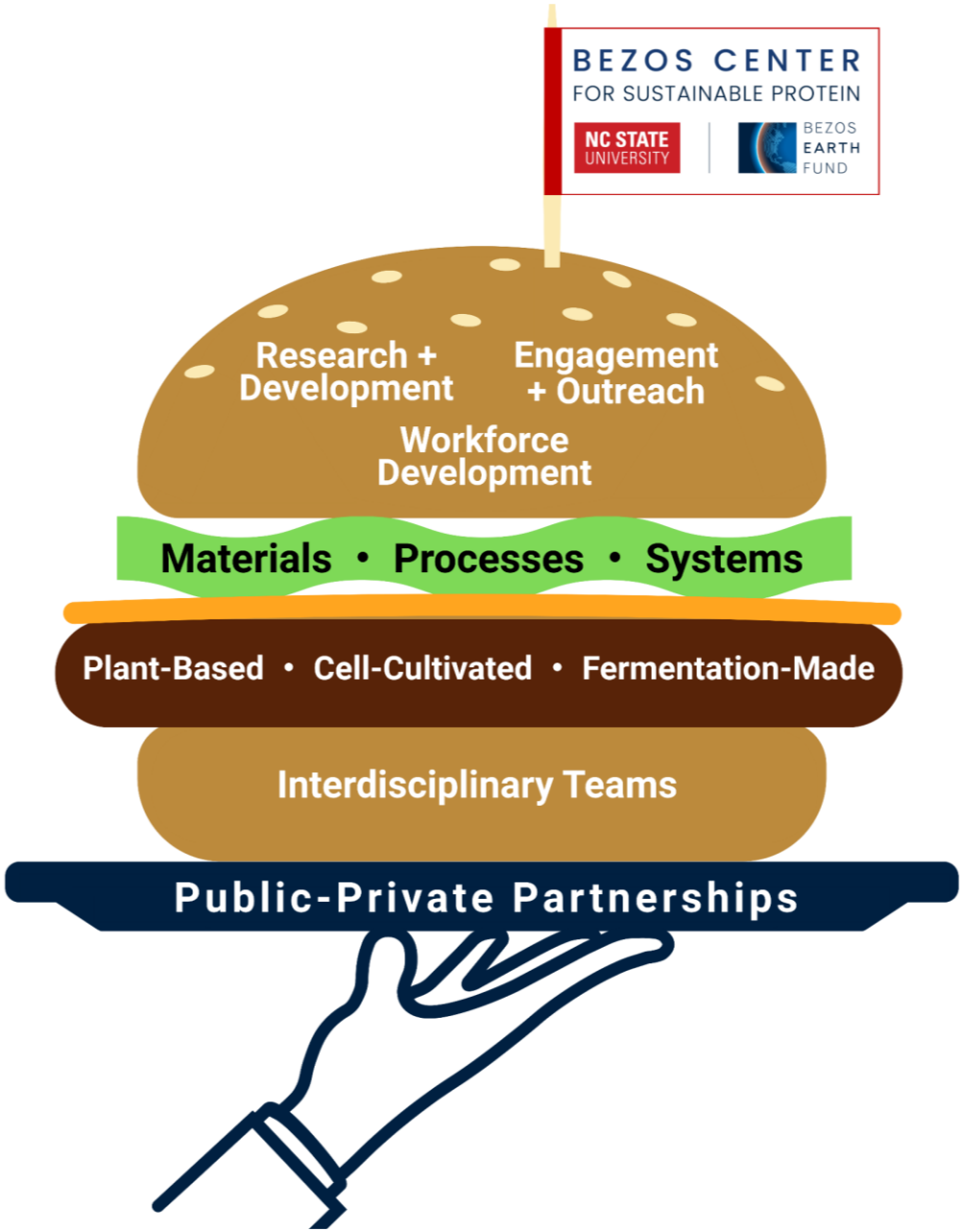
9-11 June 2026 |
Copenhagen, Denmark

A Systems-level Overview of Alternative Proteins

Rohan A. Shirwaiker

James T. Ryan Distinguished Professor in Industrial & Systems Engineering

Director of Bezos Center for Sustainable Protein at North Carolina State University



BRIDGE2FOOD EUROPE

9-11 June 2026 |
Copenhagen, Denmark

A Systems-level Overview of Alternative Proteins

AGENDA:

- Proteins: composition, sourcing, and diversification
- Plant-based, cell-cultivated, and fermentation-made protein platforms
- Cross-cutting considerations and tools

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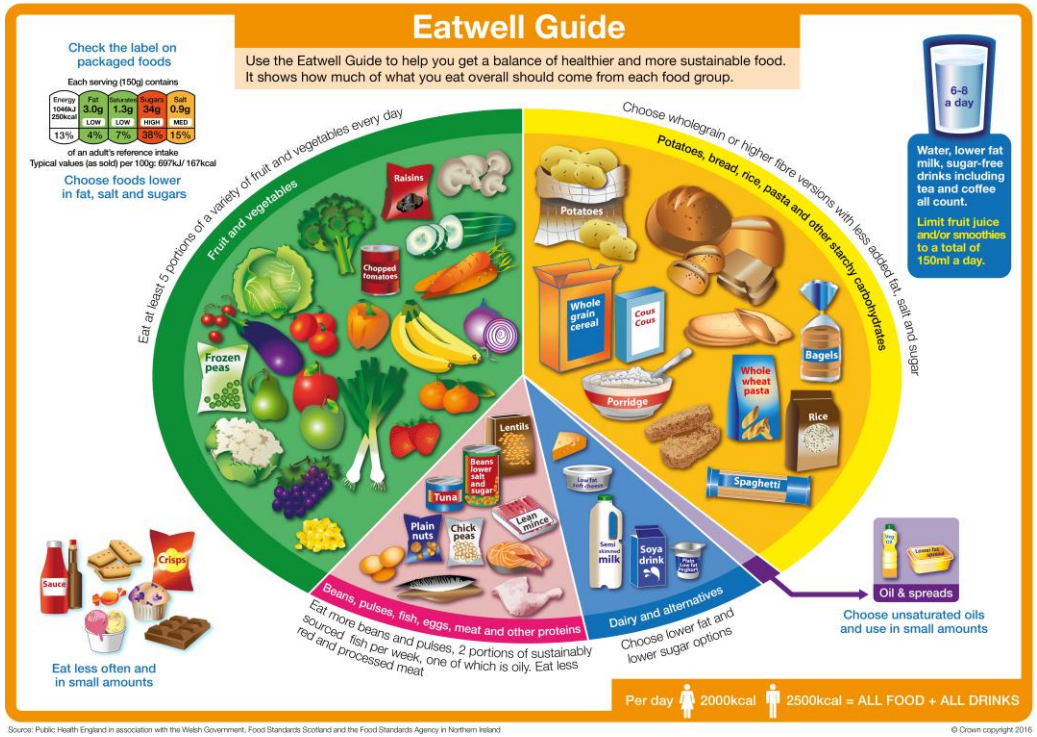
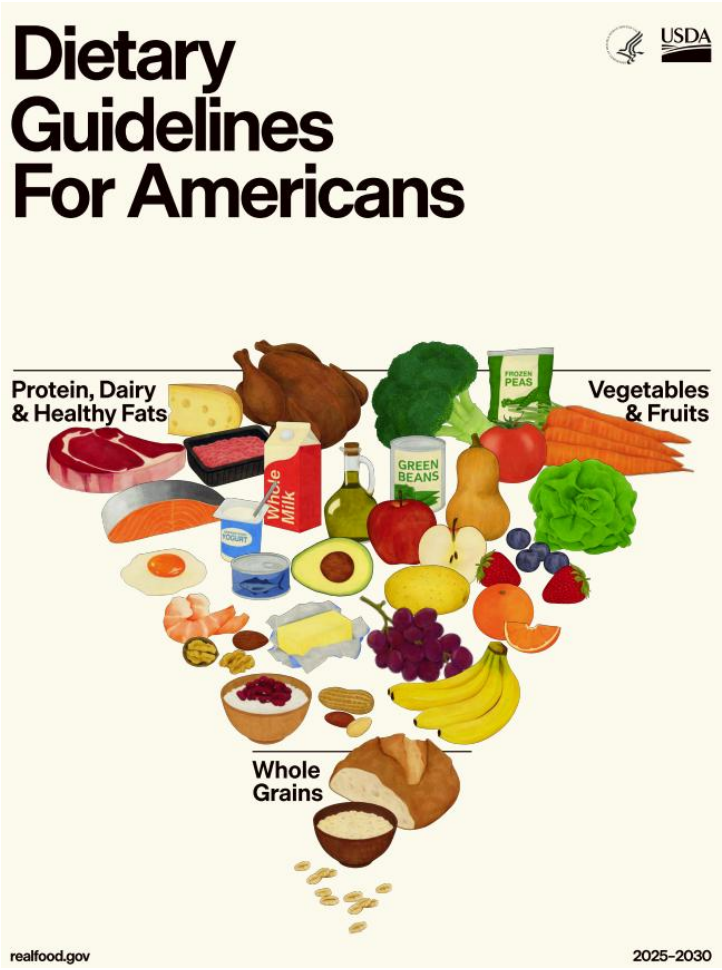
Food = Macros + Micros + Water

BRIDGE2FOOD EUROPE

https://en.foedevarestyrelsen.dk/food/nutrition-and-health/the-official-dietary-guidelines



https://www.gov.uk/government/publications/the-eatwell-guide



https://cdn.realfood.gov/DGA.pdf

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Food = Macros + Micros + Water

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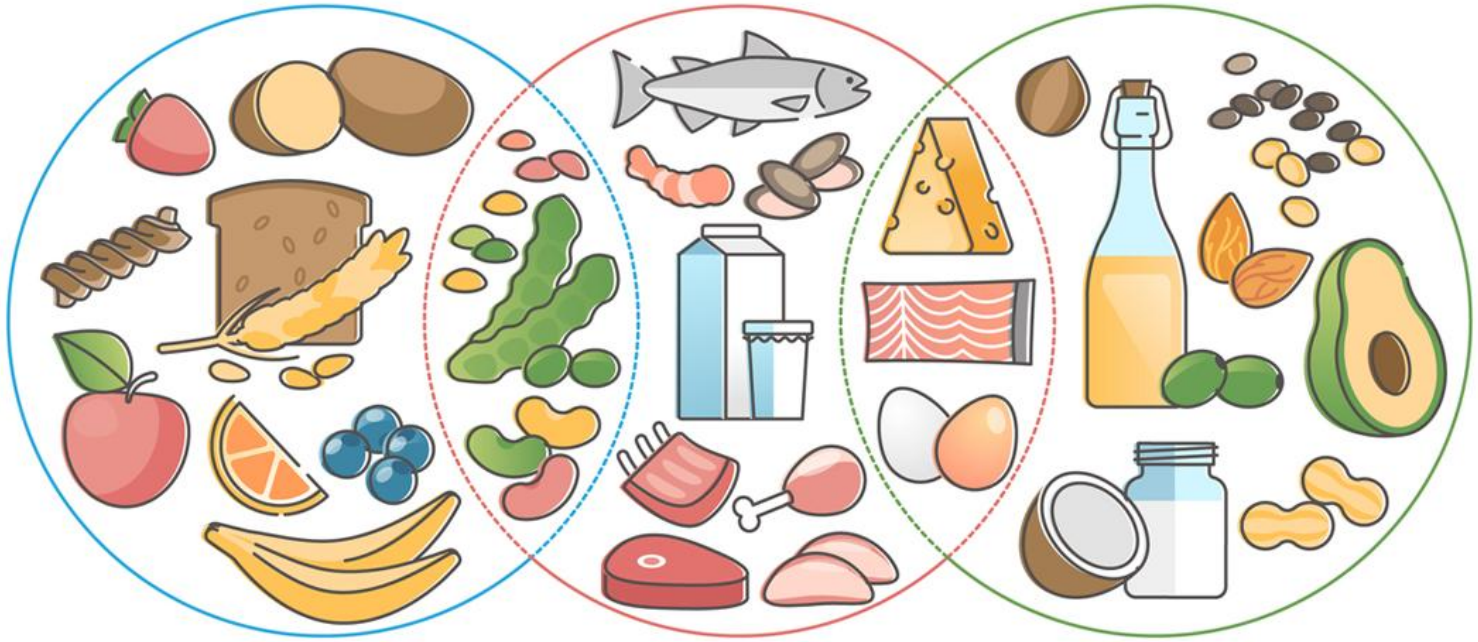

	Carbohydrates	Proteins	Fats
Acceptable Macronutrient Distribution Range (AMDR):	45-65%	10-35%	20-35% (saturated fat < 10%)
Caloric content	4 cal/g	4 cal/g	9 cal/g

Institute of Medicine. Dietary Reference Intakes for Energy, Carbohydrate, Fiber, Fat, Fatty Acids, Cholesterol, Protein, and Amino Acids. National Academies Press, 2005.

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Proteins → Amino Acids

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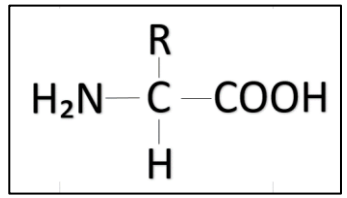
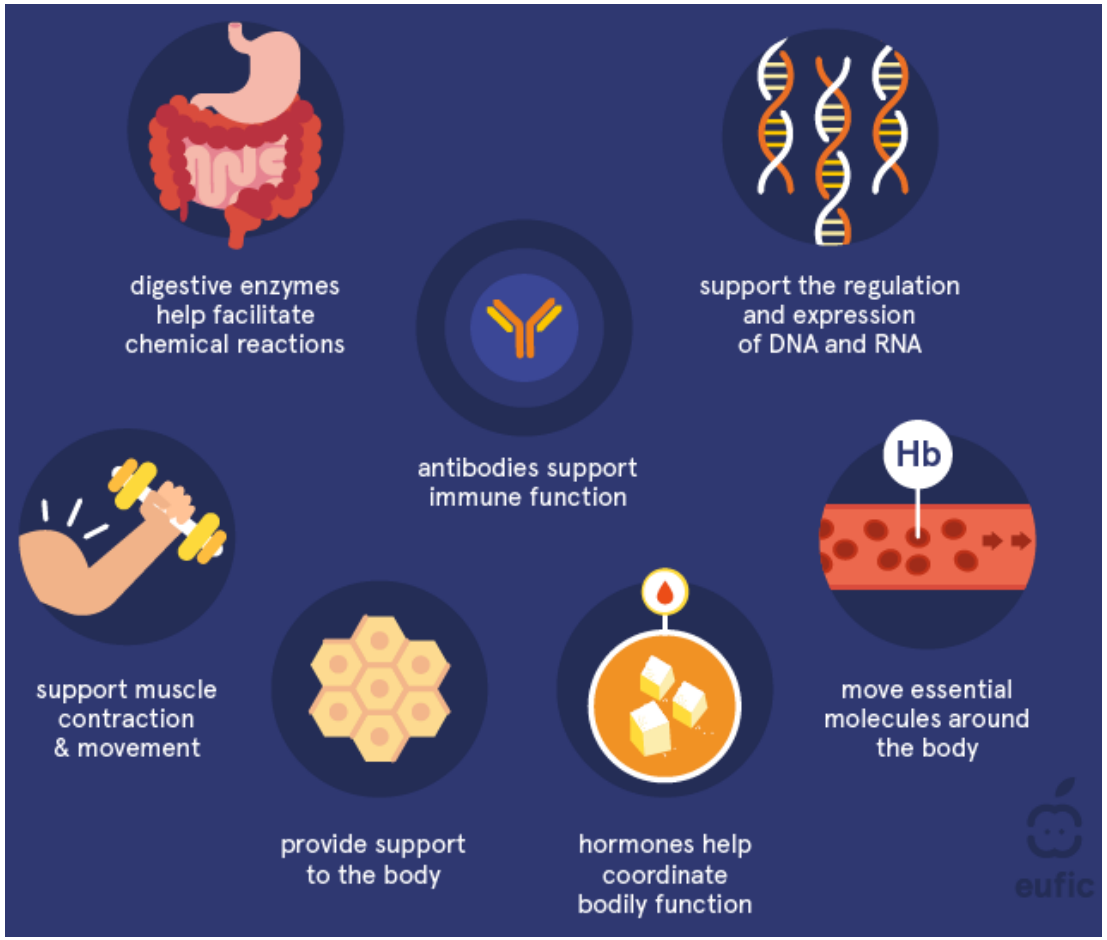
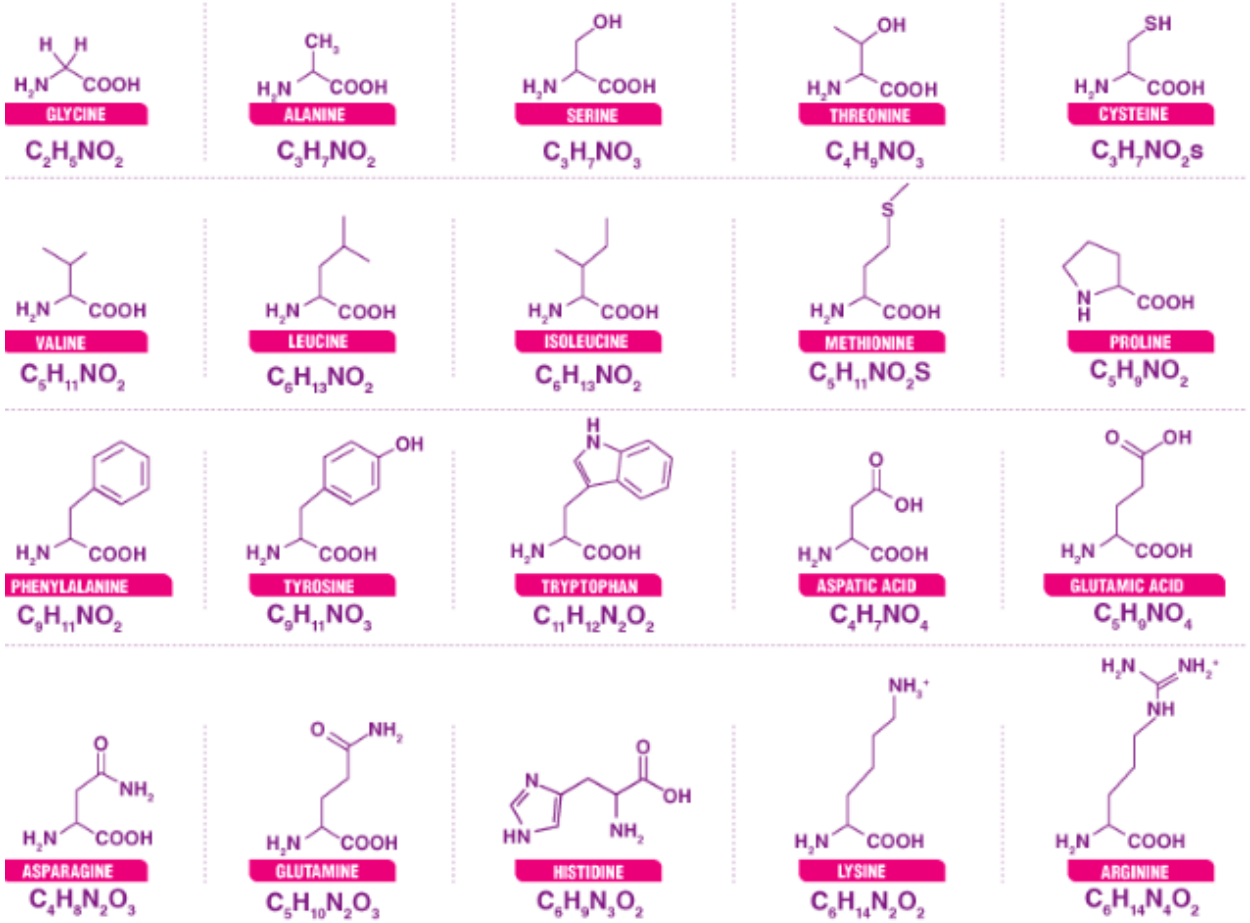
- Building blocks of proteins: Amino acids
- 500+ amino acids occur in nature, but humans use 20 standard amino acids to build most proteins.





https://www.eufic.org/en/whats-in-food/article/what-are-proteins-and-what-is-their-function-in-the-body



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Proteins → Amino Acids

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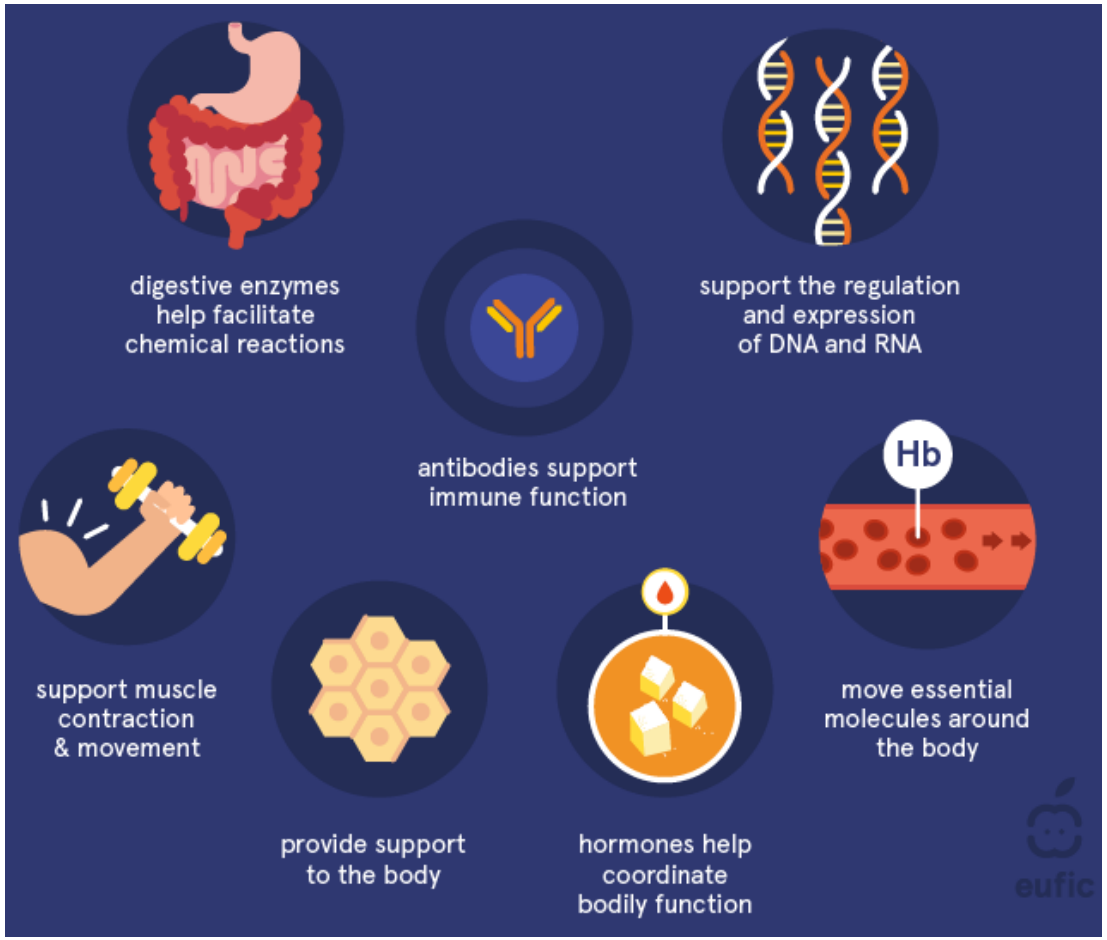
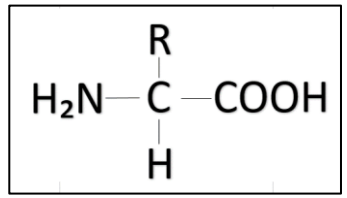
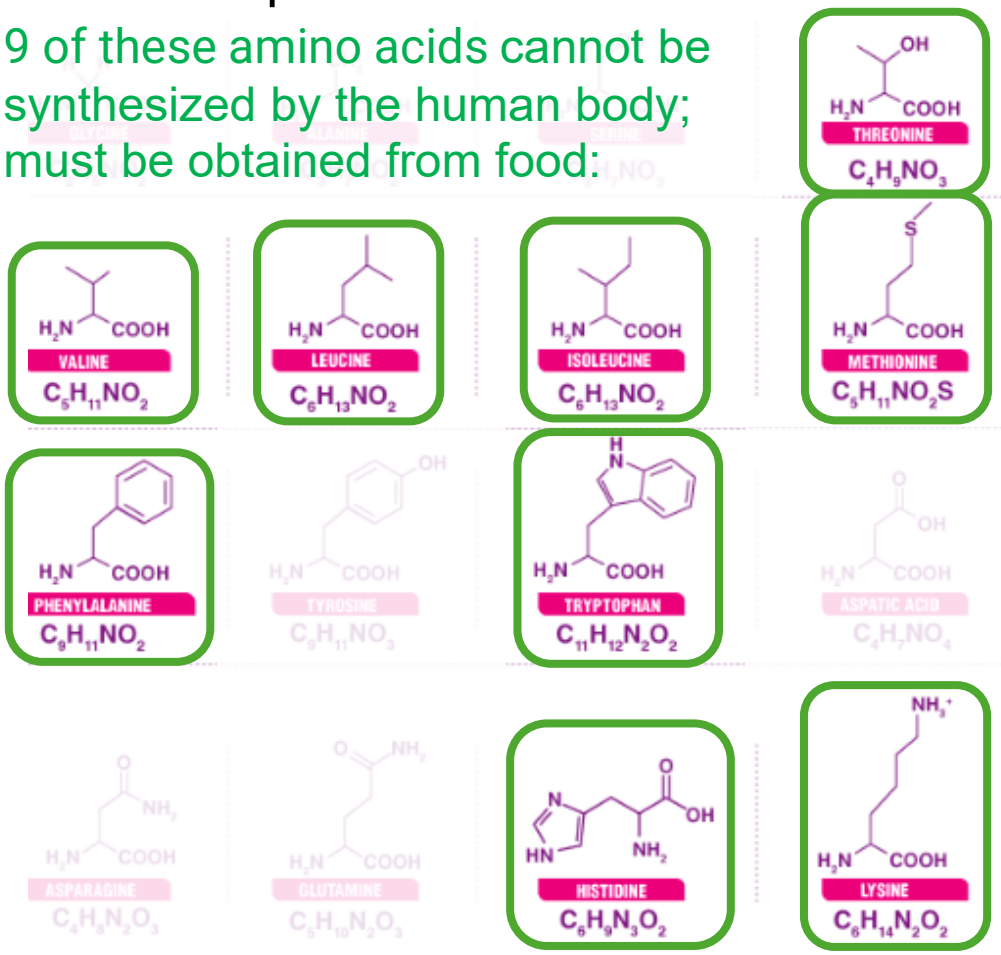


https://www.eufic.org/en/whats-in-food/article/what-are-proteins-and-what-is-their-function-in-the-body

- Building blocks of proteins: Amino acids
- 500+ amino acids occur in nature, but humans use 20 standard amino acids to build most proteins.
- 9 of these amino acids cannot be synthesized by the human body; must be obtained from food:





Complete Protein

Foods containing all 9 essential amino acids

- **Primarily animal-based:** Meat, poultry, eggs, dairy, seafood
- **Some plant-based sources:** Soy, quinoa, buck wheat, chia seeds, blue-green algae

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Global Trends in Protein Consumption

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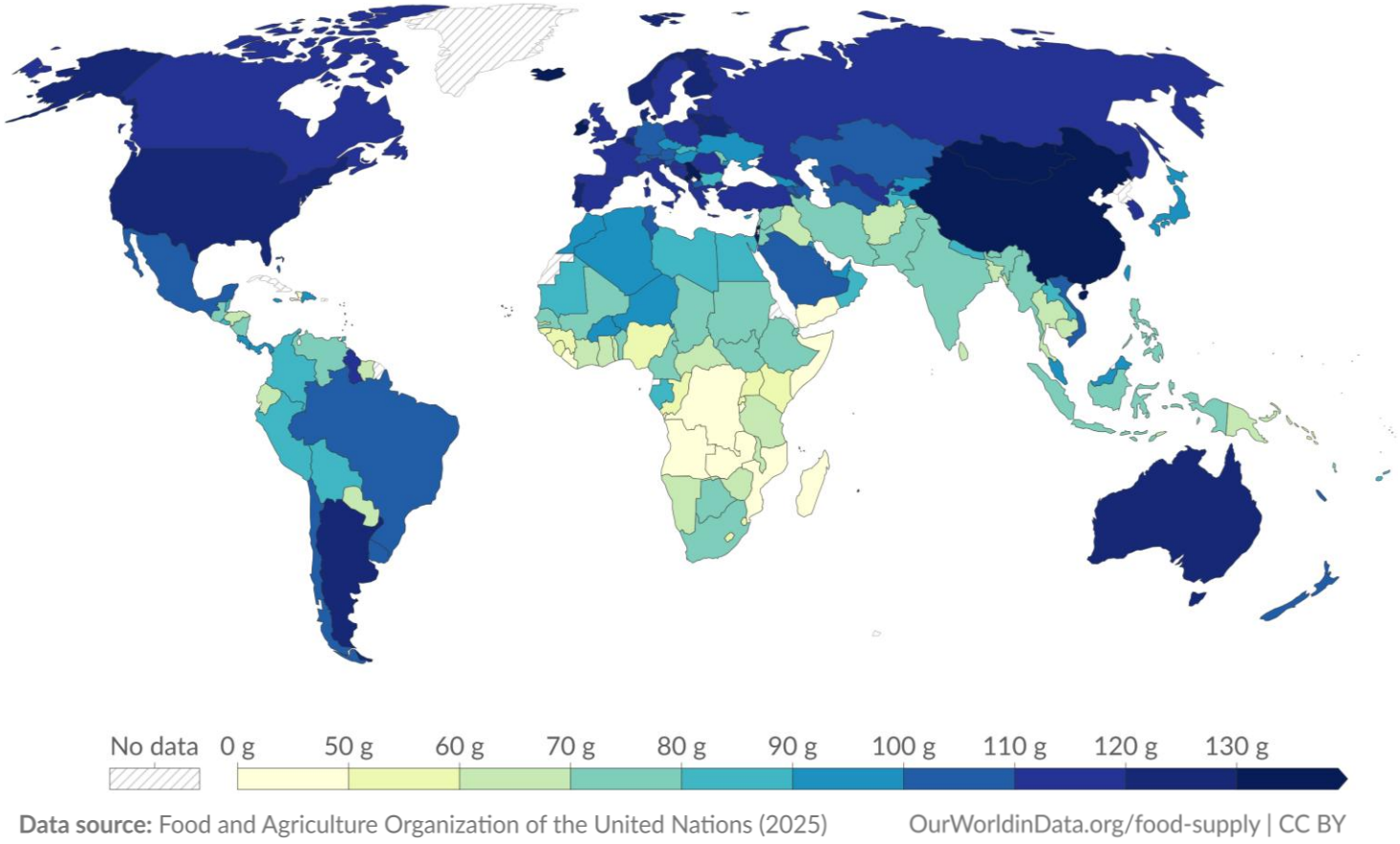
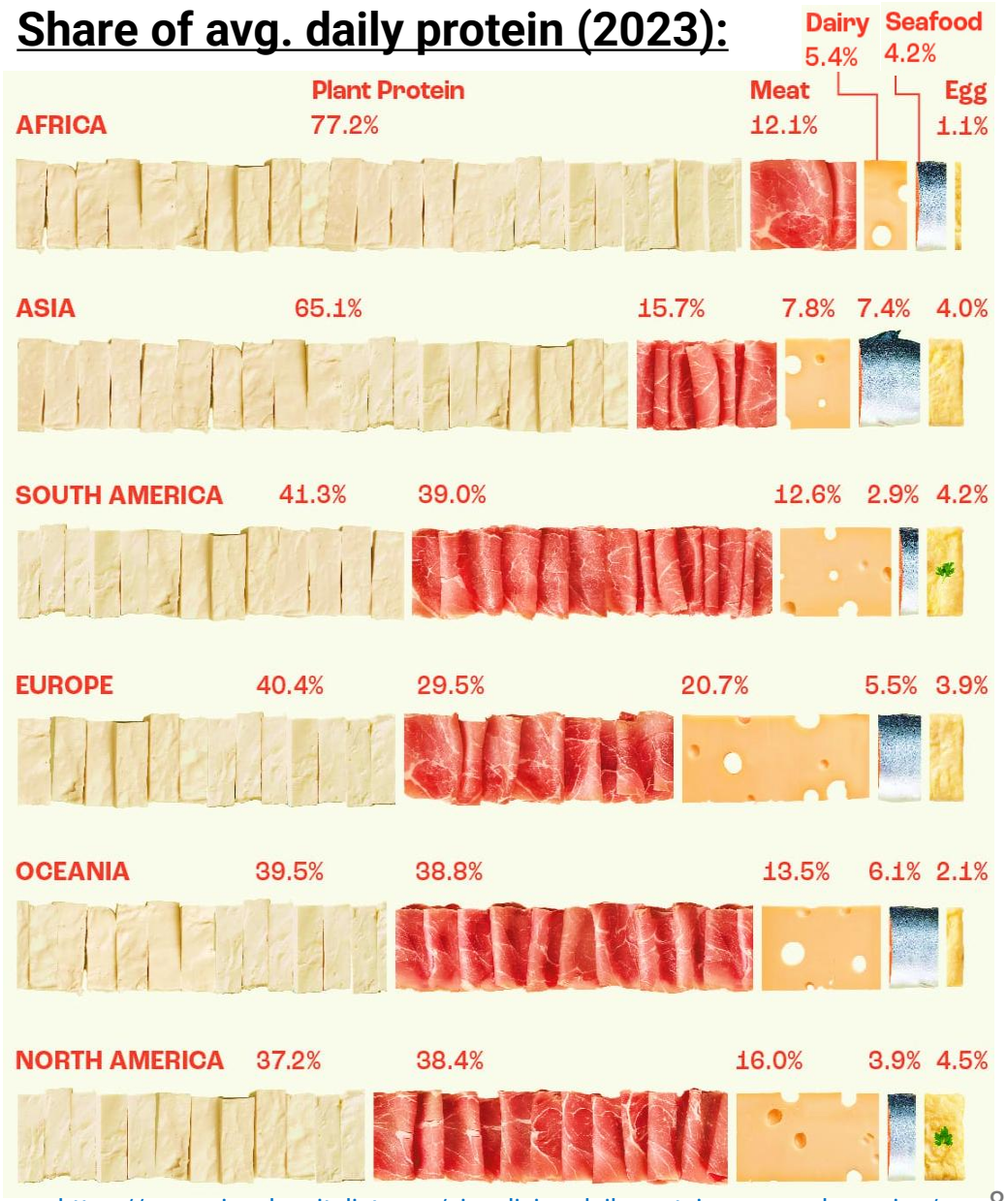
Daily per capita protein supply (2023):

Grams of protein delivered to household; does not necessarily indicate quantity of protein actually consumed (food may be wasted at the consumer level).



https://ourworldindata.org/grapher/daily-per-capita-protein-supply

Share of avg. daily protein (2023):



https://www.visualcapitalist.com/visualizing-daily-protein-sources-by-region/

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Global Trends in Meat Production

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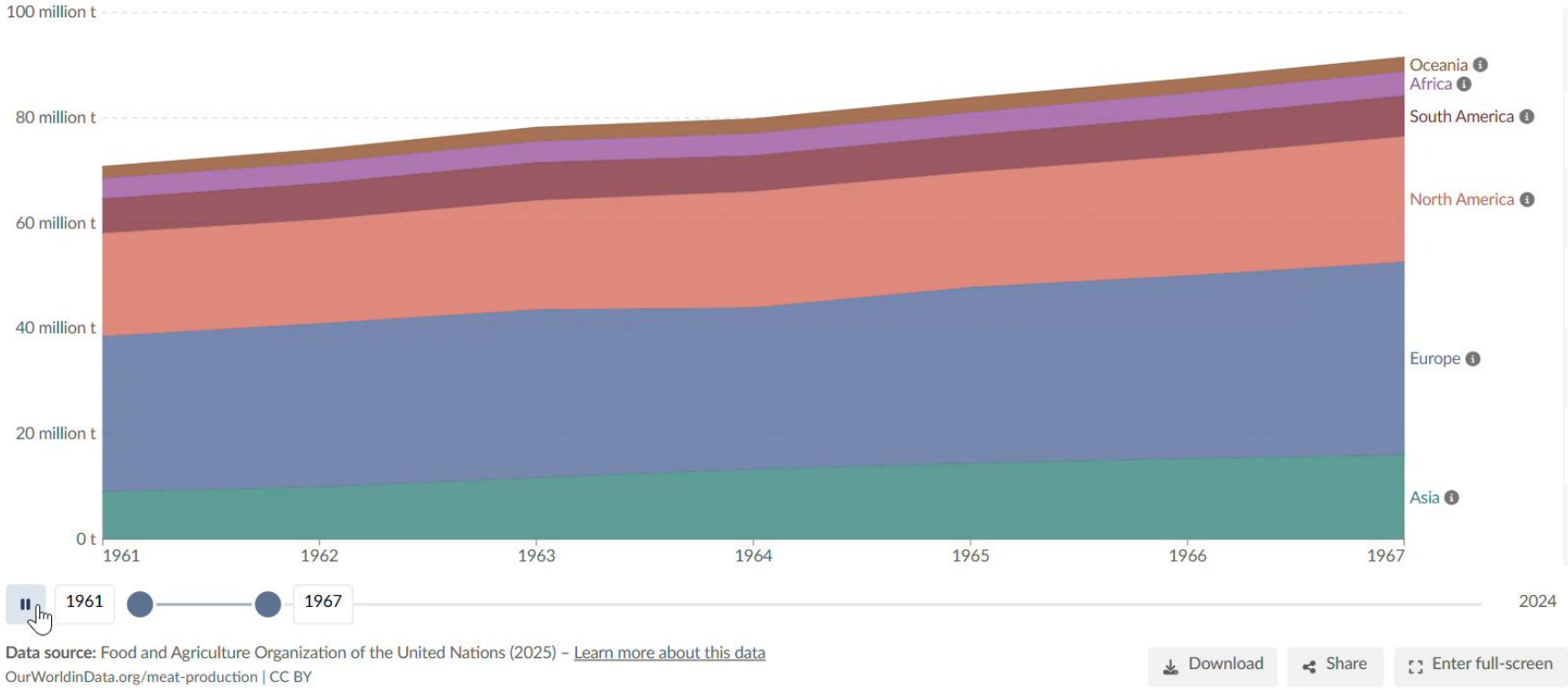
Global meat production in tonnes (1961-2024):

Includes cattle, poultry, sheep/mutton, goat, pigmeat, and wild game

Our World in Data



Country or region	1961–2024	↑ Relative Change
Asia		+1,726%
South America		+634%
Africa		+518%
Oceania		+234%
North America		+228%
Europe		+119%

https://ourworldindata.org/meat-production

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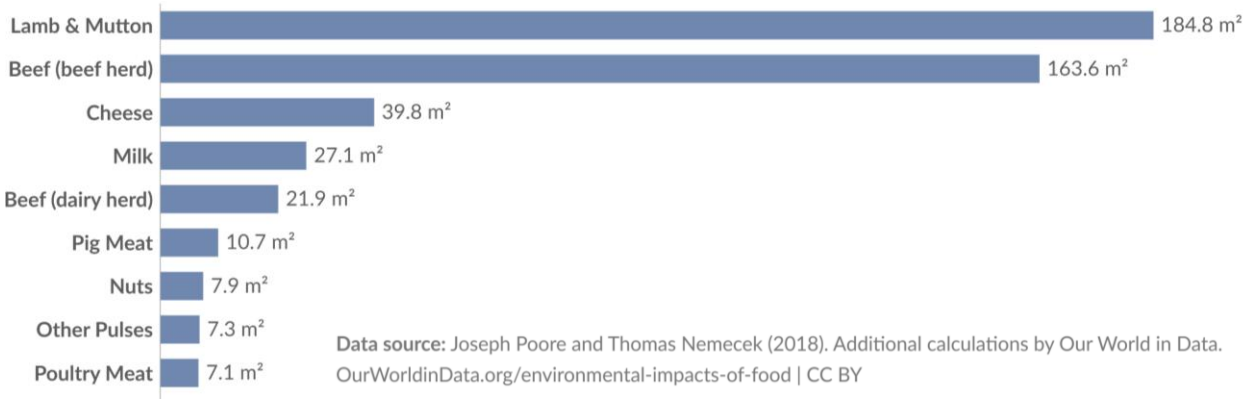
Need for Food Protein Diversification

BRIDGE2FOOD EUROPE

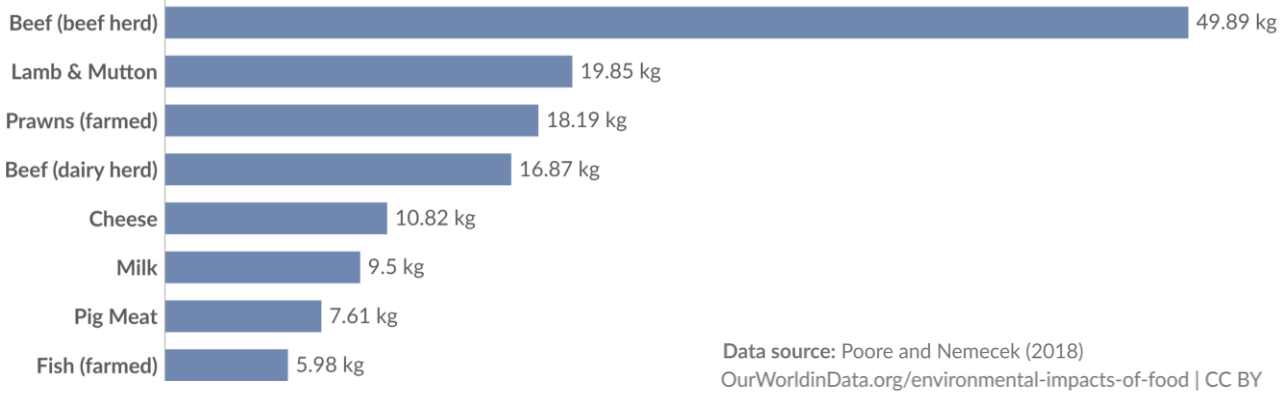
Land use per 100 grams of protein (2018):



Data source: Joseph Poore and Thomas Nemecek (2018). Additional calculations by Our World in Data.
OurWorldinData.org/environmental-impacts-of-food | CC BY

Our World in Data

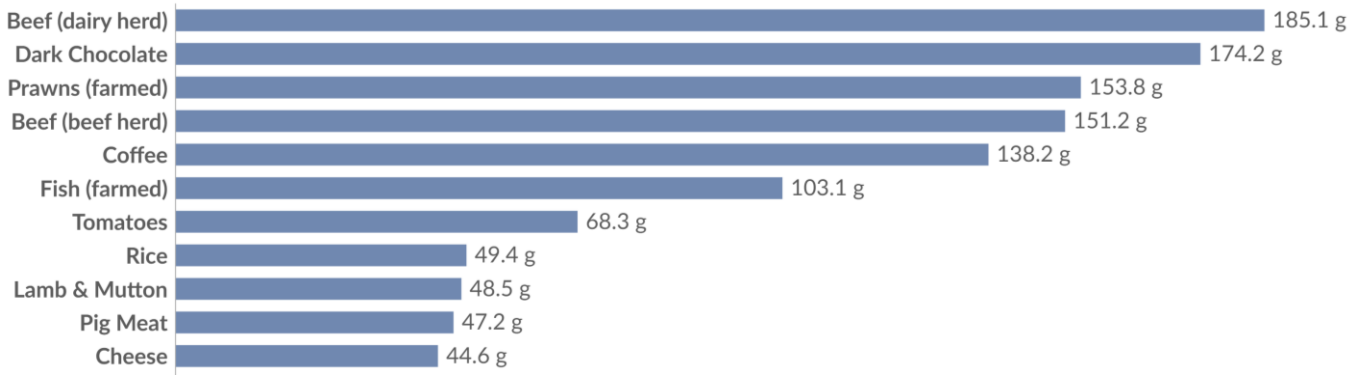
GHGe per 100 grams of protein (2018):



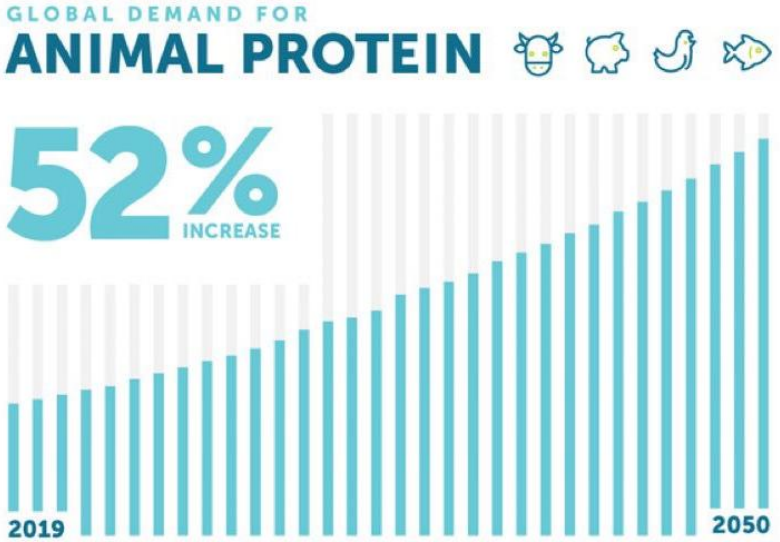
Data source: Poore and Nemecek (2018)
OurWorldinData.org/environmental-impacts-of-food | CC BY

Eutrophying emissions per 100 grams of protein (2018):

Runoff of excess nutrients (grams of PO_4eq) into the surrounding environment and waterways, which affects and pollutes ecosystems



Data source: Joseph Poore and Thomas Nemecek (2018). Additional calculations by Our World in Data.
OurWorldinData.org/environmental-impacts-of-food | CC BY



https://ourworldindata.org/environmental-impacts-of-food

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Food Security × Planetary Health

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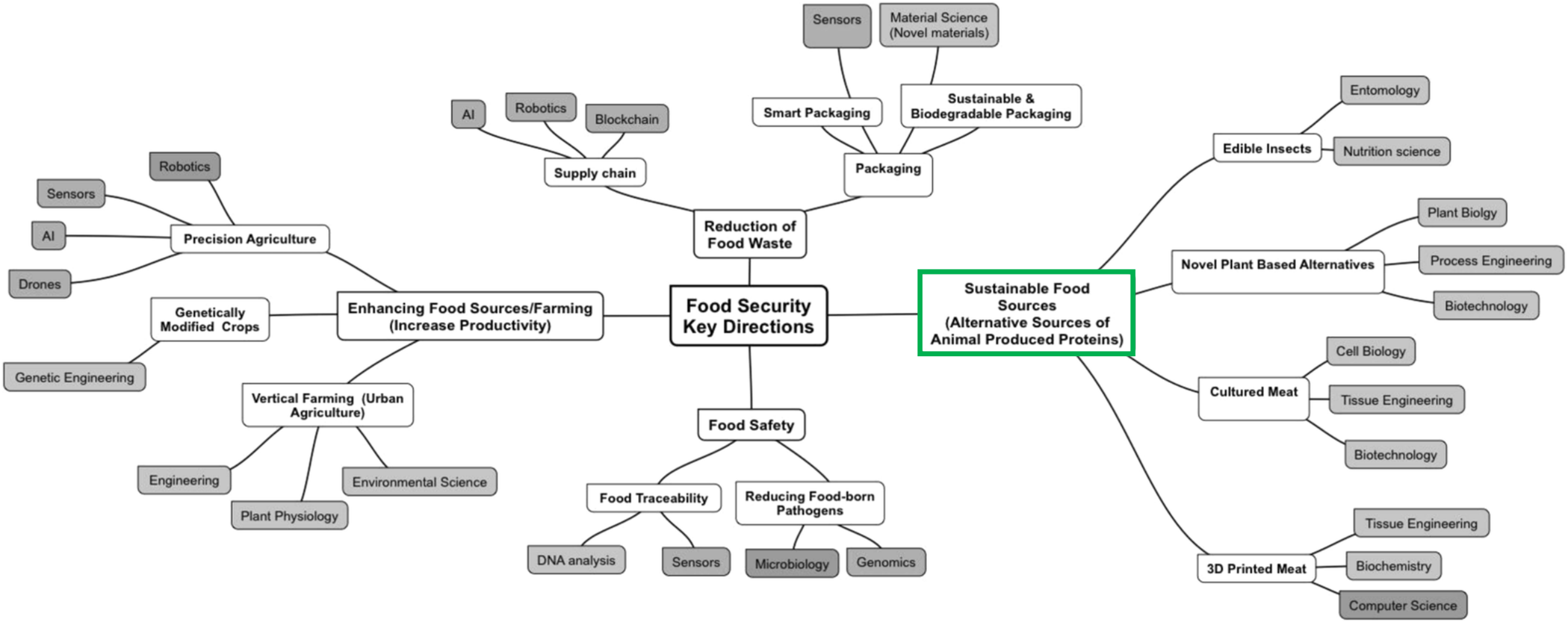

Lurie-Luke (2024) Alternative protein sources: science powered startups to fuel food innovation. *Nature Communications*, 15: 4425.

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Food Protein Diversification

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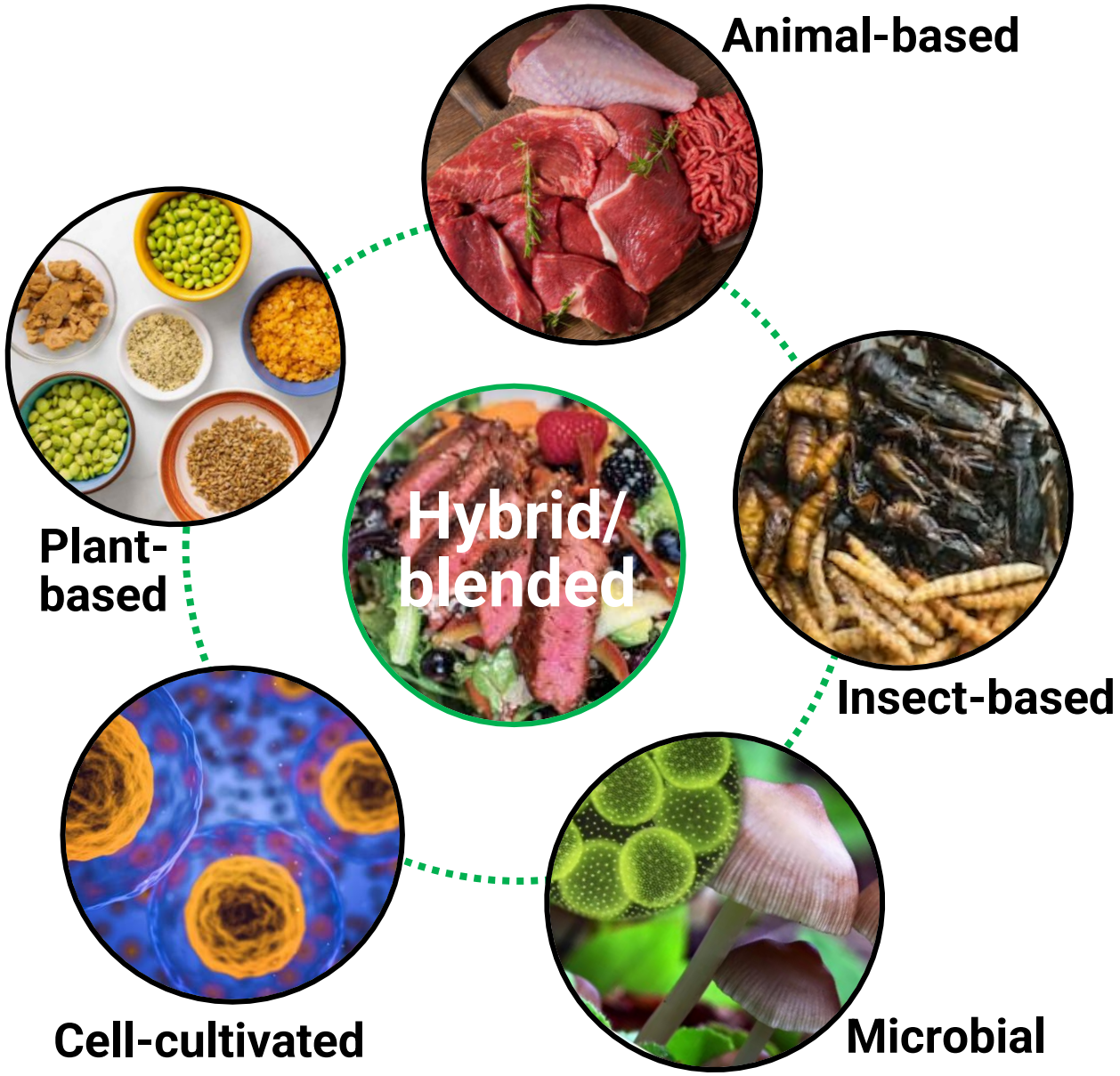

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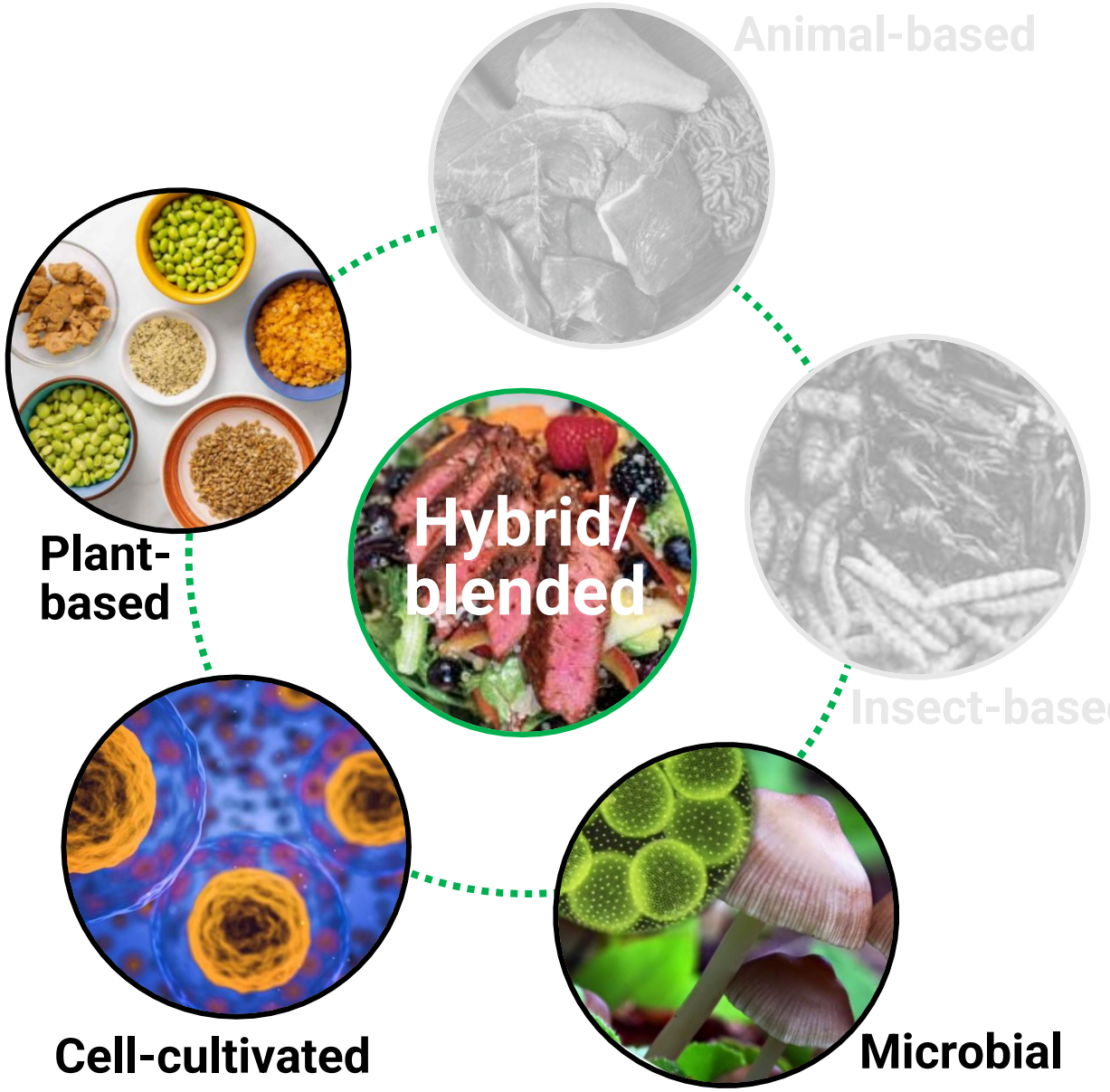
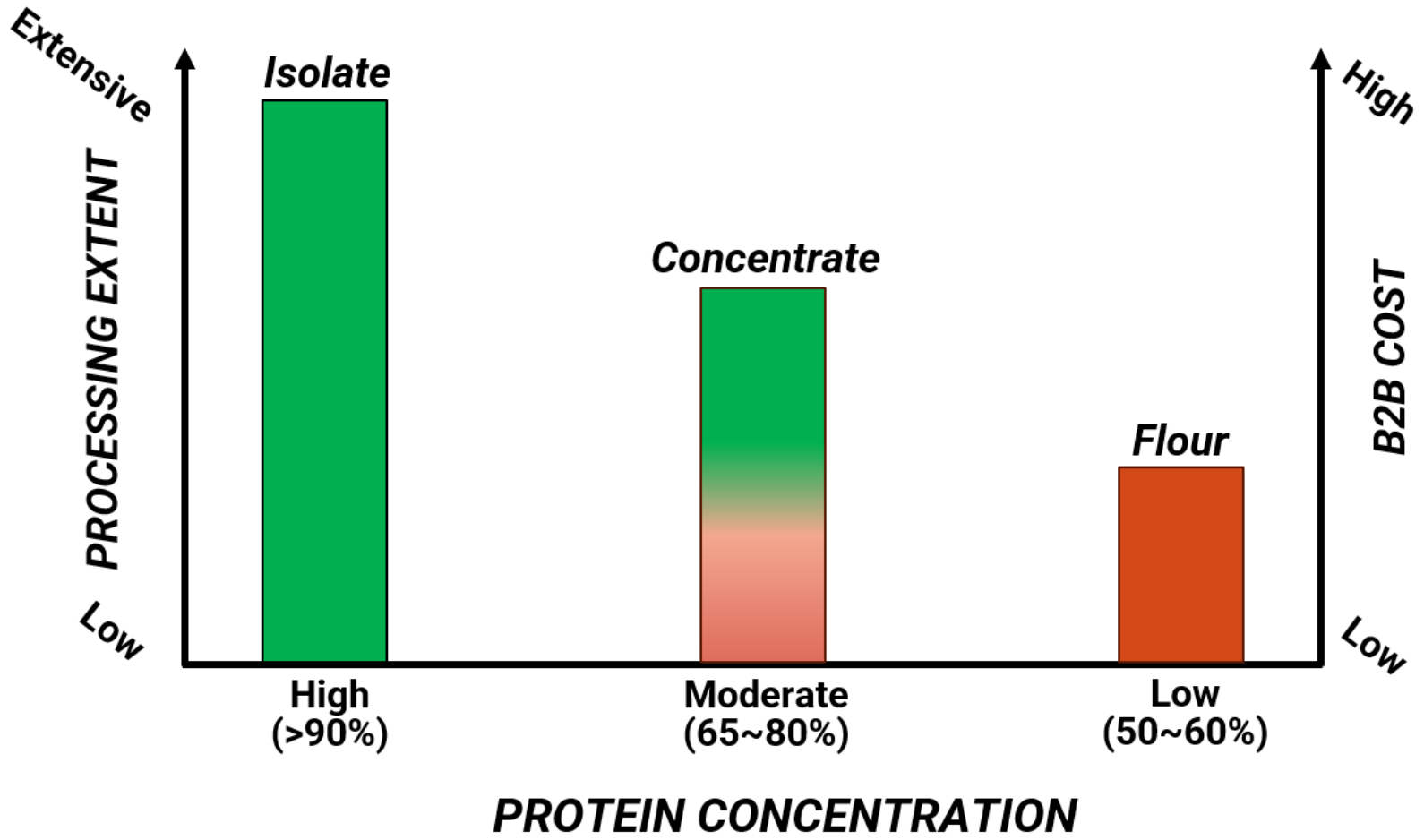
Food Protein Diversification

BRIDGE2FOOD EUROPE



Plant-based Proteins



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Plant-based Proteins

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SEED COMPANY

CULTIVATION

PRE-EXTRACTION
Harvest

FRACTIONATION
Milling/Grinding

EXTRACTION
Air classification
Alkalization/Acidification

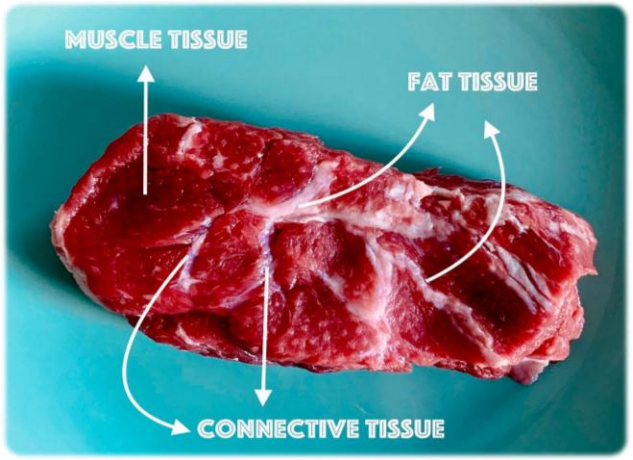
Filtration
Membrane/Ion Exchange

DRYING

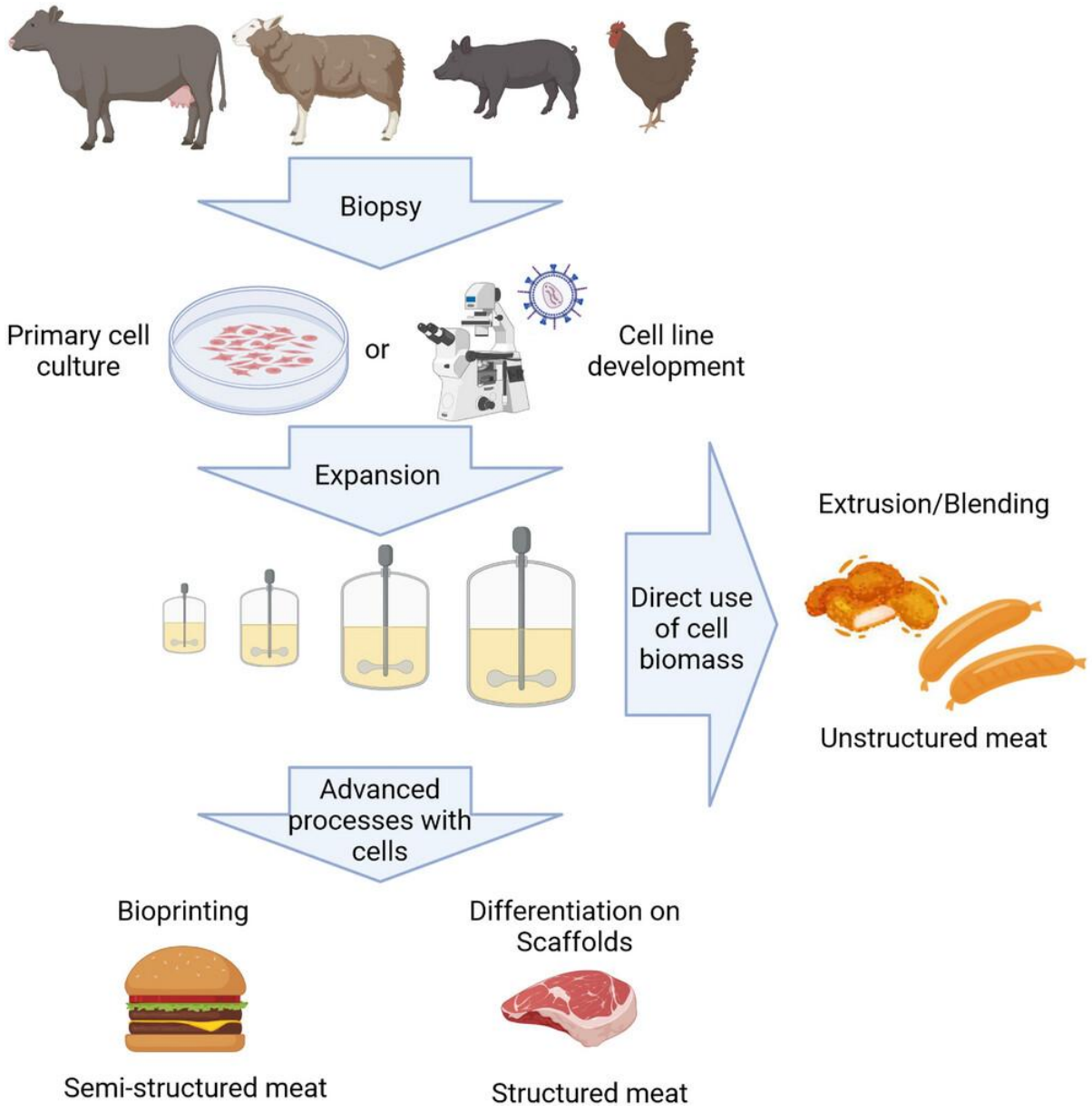
FOOD PROCESSING

Aimutis WR, Shirwaiker RA (2025) The challenges of co-extraction of animal and plant proteins from transgenic plants for use in food and feed. *Front. Plant Sci.* 16:1626856

Cell-cultivated Proteins



Meat component	Initial function	Culinary contribution to meat	Cultivated meat component
Muscle	Contraction/ movement	Texture, biomass	Muscle cells
Fat	Storage of energy, role in signaling	Contribution of flavor substances, juiciness, texture	Adipocytes
Connective tissue	Structure, support, protection	Texture, biomass	Non/Fibroblasts
ECM	Structure, tissue homeostasis/cell-matrix interactions	Texture, biomass	Natural and synthetic scaffolds
Blood vessels	Oxygen and nutrients supply, metabolite removal	Color, flavor	Recombinant heme proteins, food dye, beet juice



https://medium.com/cookemistry/beef-101-part-i-ee877bc7bf8c

Kirsch M, Morales-Dalmau J, Lavrentieva A. Cultivated meat manufacturing: Technology, trends, and challenges. *Eng Life Sci*. 2023; 23:e2300227.

Cell-cultivated Proteins

Cells
- Source
- Storage
- Optimization for large-scale
- Non-gm immortalization
- Chemically induced pluripotency

Expansion
- Bioreactors
- On-line monitoring
- Harvesting
- Degradable/ Edible microcarriers

Scaffolds
- Microcarriers
- Porosity
- Vascularization
- Biodegradable materials
- Tunable properties

Media Composition
- Animal supplements
- Pharmagrade/Feed grade
- Recycling/ Methabolites withdr.
- Differentiation triggers
- Recombunant growth factor production

Differentiation
- Bioreactor Type
- Shear stress (mechanoreceptors)
- Scale-up
- Oxygen supply
- Automatization
- Monitoring of differentiation

Biopsy

Primary cell culture

or

Cell line development

Expansion

Direct use of cell biomass

Extrusion/Blending

Unstructured meat

Advanced processes with cells

Bioprinting

Semi-structured meat

Differentiation on Scaffolds

Structured meat

Kirsch M, Morales-Dalmau J, Lavrentieva A. Cultivated meat manufacturing: Technology, trends, and challenges. *Eng Life Sci*. 2023; 23:e2300227.

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Microbial Proteins

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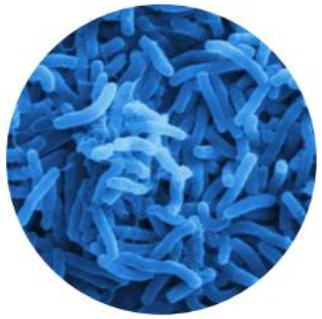
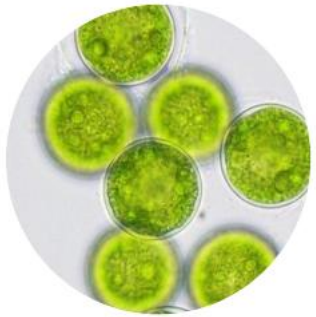


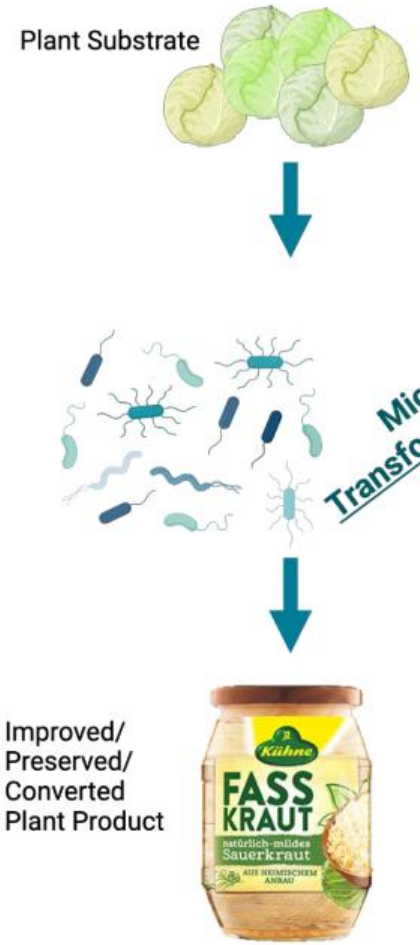
Bacteria

Yeast

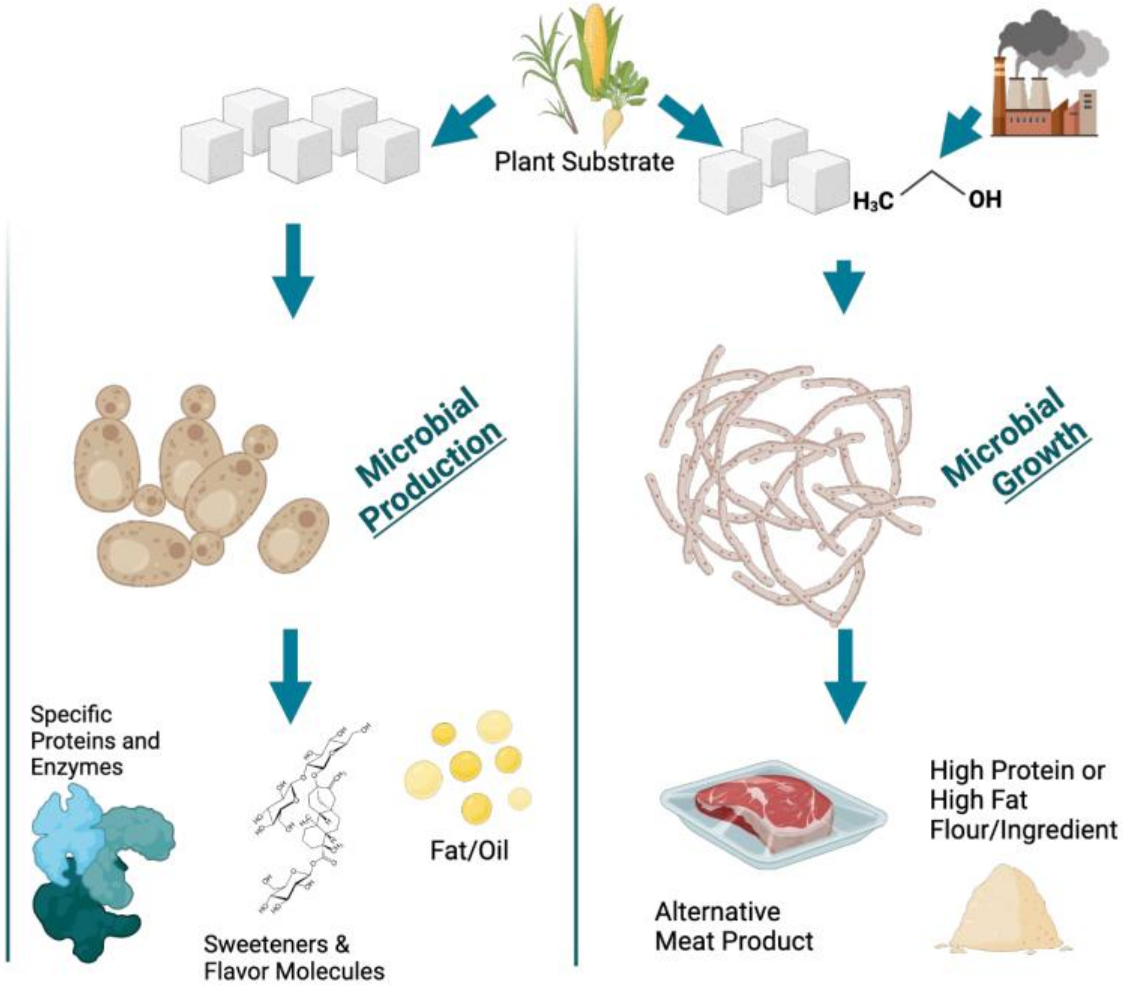
Filamentous Fungi



Algae



Traditional Fermentation

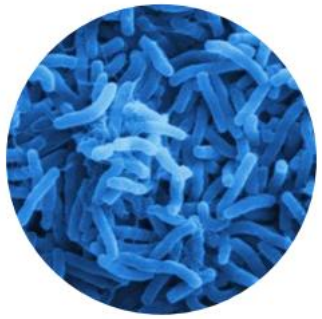


Precision Fermentation

Biomass Fermentation

https://gfi.org/science/the-science-of-fermentation/
Courtesy: Dr. Adam Leman, Principal Scientist – Fermentation, GFI

Microbial Proteins



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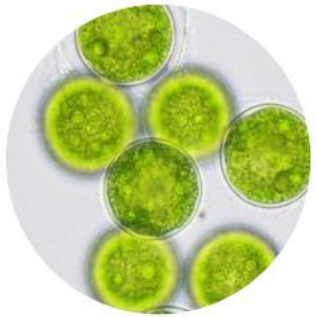
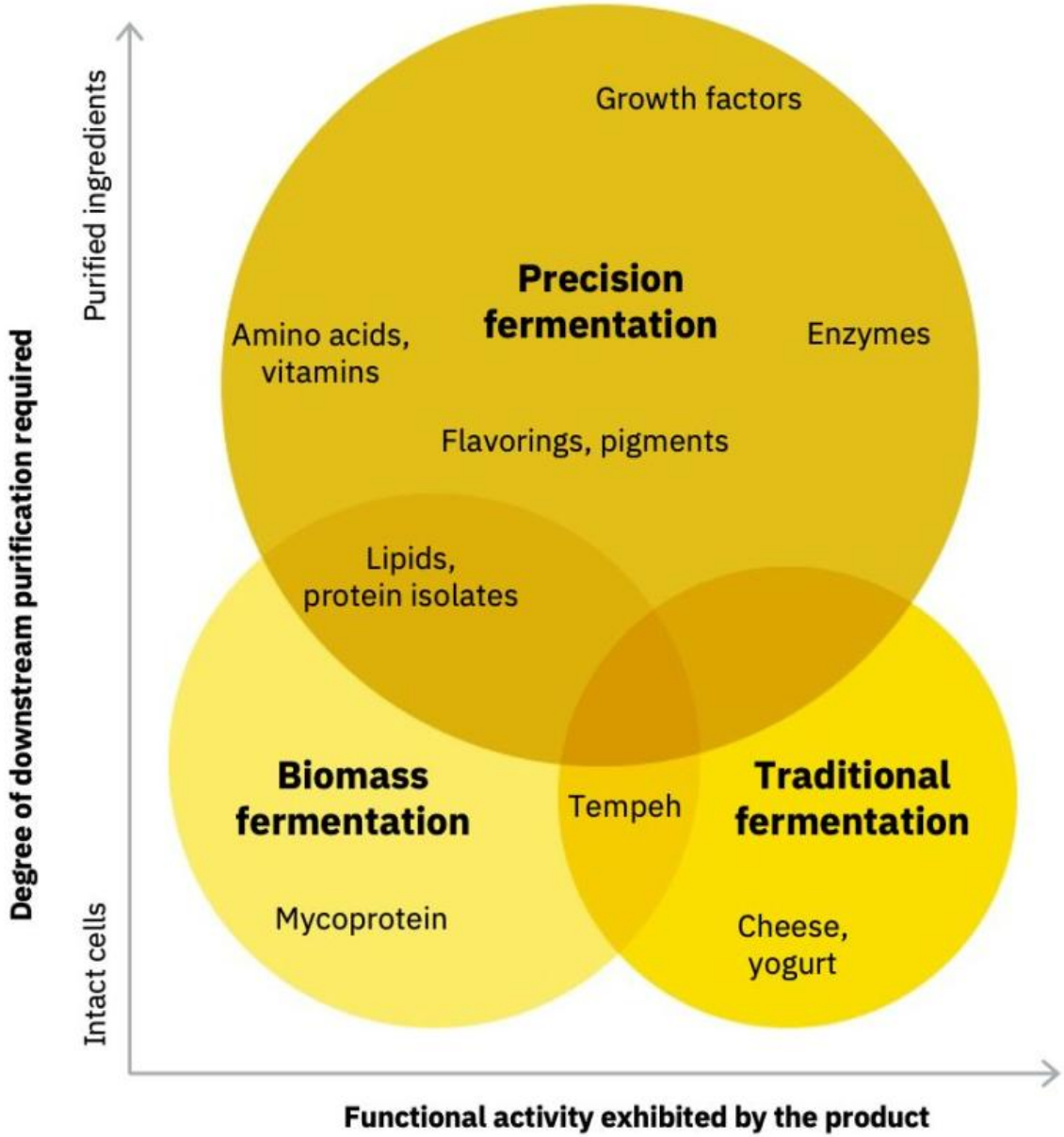


Algae



https://gfi.org/science/the-science-of-fermentation/
Courtesy: Dr. Adam Leman, Principal Scientist – Fermentation, GFI

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Microbial Proteins

Fermentation is a relatively mature platform, but alternative protein applications present new challenges

Feedstock optimization

FEEDSTOCK OPTIMIZATION

Any source of biomass can serve as a feedstock for fermentation-based protein production

STRAIN DEVELOPMENT

The cells are optimized for fermentation and final product function via selection and/or cell engineering.

Strain development

FERMENTATION BIOPROCESS DESIGN

The cells are added to a cultivator, which can be open or closed, along with liquid or solid feedstocks.

The cells digest the feedstock to support their growth. In the process, they may also serve as a miniature production factory for specific desirable ingredients.

Bioprocess design

Formulation and manufacturing

BULK AND SPECIALTY FINAL PRODUCTS

The whole cell biomass or fractions thereof can be harvested to produce bulk ingredients.
In some cases, the feedstock *and* the microbial biomass comprise the final product.

Bioconverted feedstocks

Microbial biomass

Alternatively, a specific protein or other high-value ingredient produced by the cells can be isolated and purified. for other bioprocess or applications.

Functional ingredients

Finally, sidestreams like cells and spent media can be valorized for other bioprocesses and applications.

Target selection and design

https://gfi.org/science/the-science-of-fermentation/
Courtesy: Dr. Adam Leman, Principal Scientist – Fermentation, GFI

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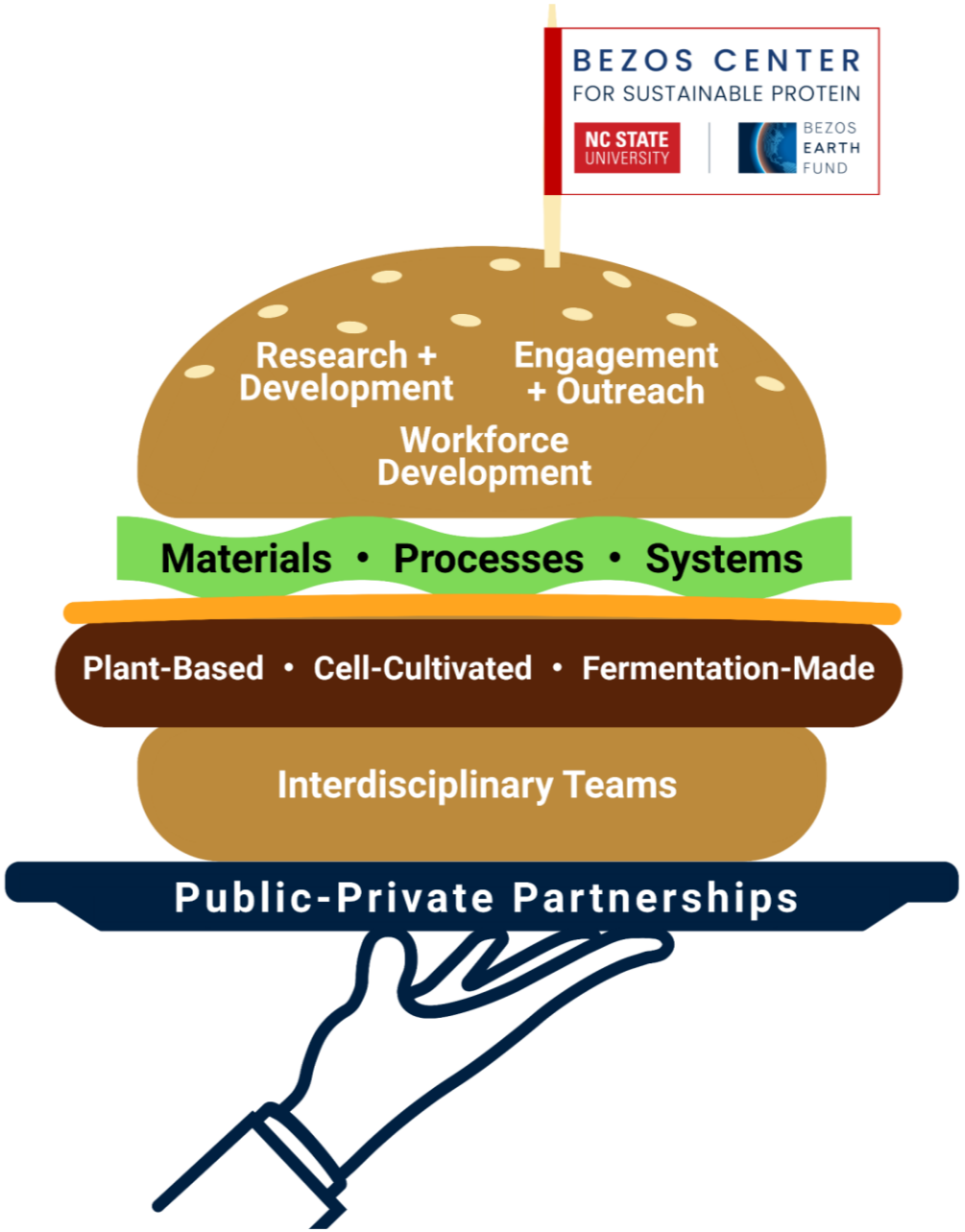
Critical cross-cutting considerations for successful alternative protein product development and translation

- Taste × Price × Convenience
- Supply chain robustness
- Lifecycle analysis
- Techno economic analysis
- Regulatory process



Thank you

https://bezoscenter.ncsu.edu

bezoscenter@ncsu.edu