



Beyond omics: From descriptive profiling to causal and scalable design of fermentation microbiomes

Dongze Niu¹, Huili Pang², Xuekai Wang³, Liang Song⁴, Jing Zhang⁵, Ansah Terry⁶, Junfeng Li⁷, Jingwen Cao⁸, Qinhua Liu⁹, Dayong Han⁴, Jidong Wang², Jong Geun Kim¹⁰, Kazuo Ataku¹¹, Smerjai Bureenok¹², Zhongfang Tan², Fengyan Bai⁵, Tao Shao⁷, Taoli Huhe¹, Lifeng Wang⁵, Peijie Han⁴, Chuncheng Xu¹³, Fuyu Yang^{3, 14}, Yimin Cai²

¹Institute of Urban and Rural Mining, Changzhou University, Changzhou, China; ²School of Agriculture and Biomanufacturing, Zhengzhou University, Zhengzhou, China; ³College of Grassland Science and Technology, China Agricultural University, Beijing, China; ⁴Institute of Microbiology, Chinese Academy of Sciences, Beijing, China; ⁵College of Food Science & Engineering, Nanjing University of Finance and Economics, Nanjing, China; ⁶Department of Animal Science, University for Development Studies, P. O. Box TL1350, Tamale, Ghana; ⁷College of Agro-Grassland Science, Nanjing Agricultural University, Nanjing, China; ⁸School of Agriculture and Biology, Shanghai Jiao Tong University, Shanghai, China; ⁹Faculty of Animal Science and Technology, Yunnan Agricultural University, Kunming, China; ¹⁰Graduate School of International Agricultural Technology and Institute of Green Bio Science & Technology, Seoul National University, Pyeongchang, Korea; ¹¹Department of Dairy Science, Rakuno Gakuen University, Hokkaido, Japan; ¹²Faculty of Agricultural Innovation and Technology, Rajamangala University of Technology Isan, Nakhon Ratchasima, Thailand; ¹³College of Engineering, China Agricultural University, Beijing, China; ¹⁴School of Animal Science, Guizhou University, Guiyang, China

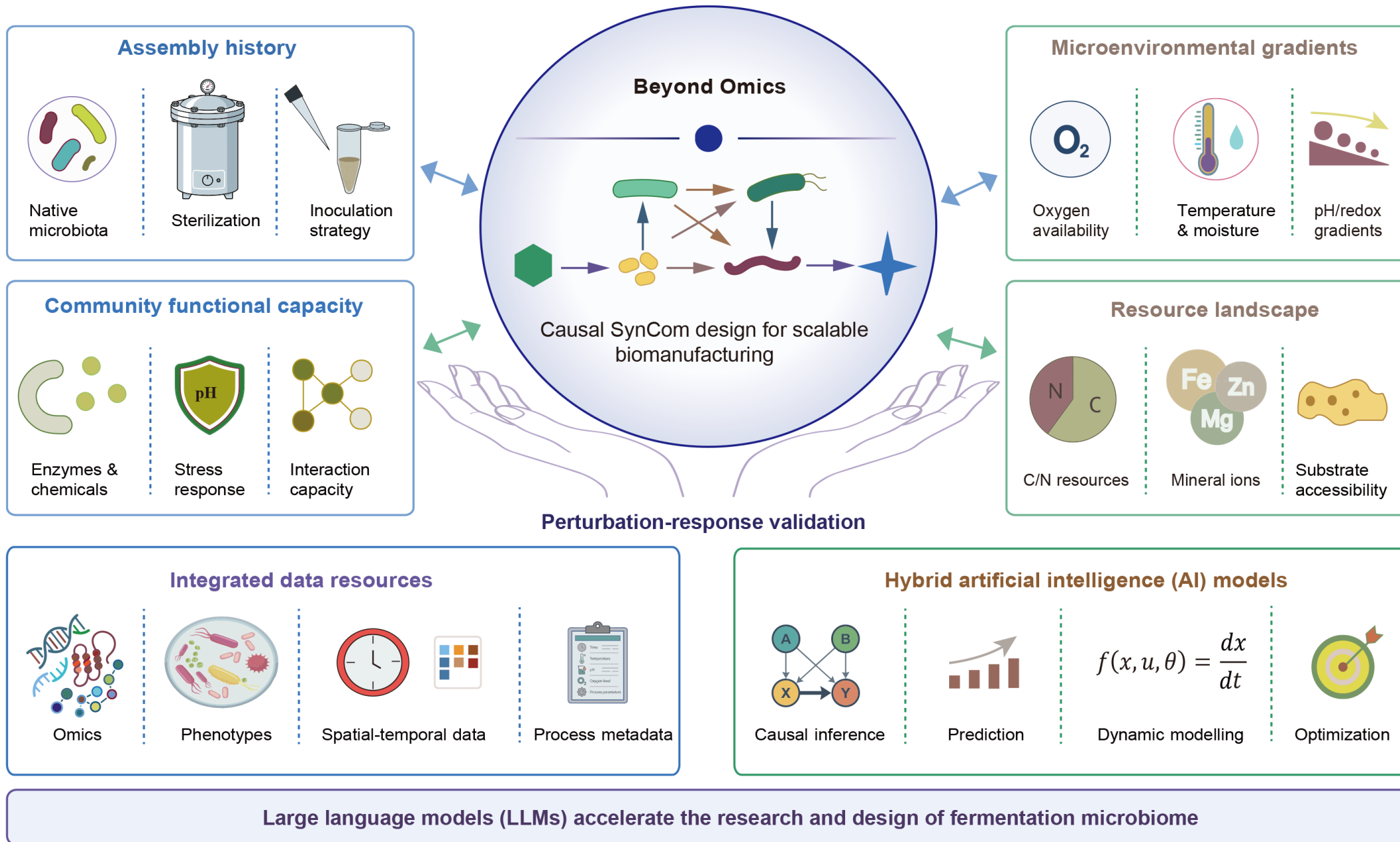


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Graphical abstract





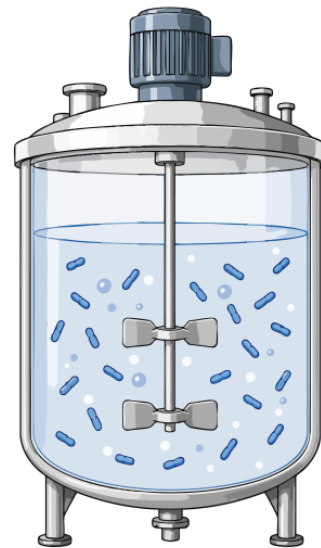
Highlights

- ❑ **From Transport Limitations to Spatial Niche Design:** Reframing spatial heterogeneity in high-solids fermentation to enable ecological niche engineering through microenvironmental and resource management.
- ❑ **From Fragmented Omics Data to Reusable Fermentation Knowledge:** Integrating multi-omics, process metadata, and phenotypic information across studies to support knowledge reuse, cross-system comparison, and predictive fermentation design.
- ❑ **From General-Purpose LLMs to Domain-Specific Tool Orchestration:** Leveraging LLMs to orchestrate specialized AI models, analytical tools, and computational workflows for intelligent biomanufacturing.



Characteristic features of different fermentation systems

(A) Industrial liquid fermentation



VS

(B) High-solids fermentation

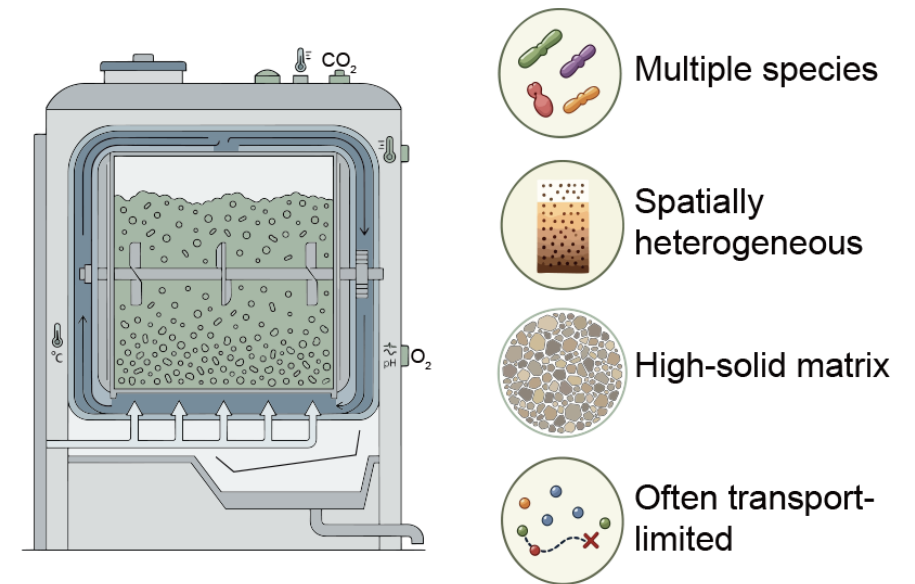


Figure 1A. Features of industrial liquid fermentation

Figure 1B. Characteristics and challenges of high-solids fermentation



Community assembly and spatial niche design

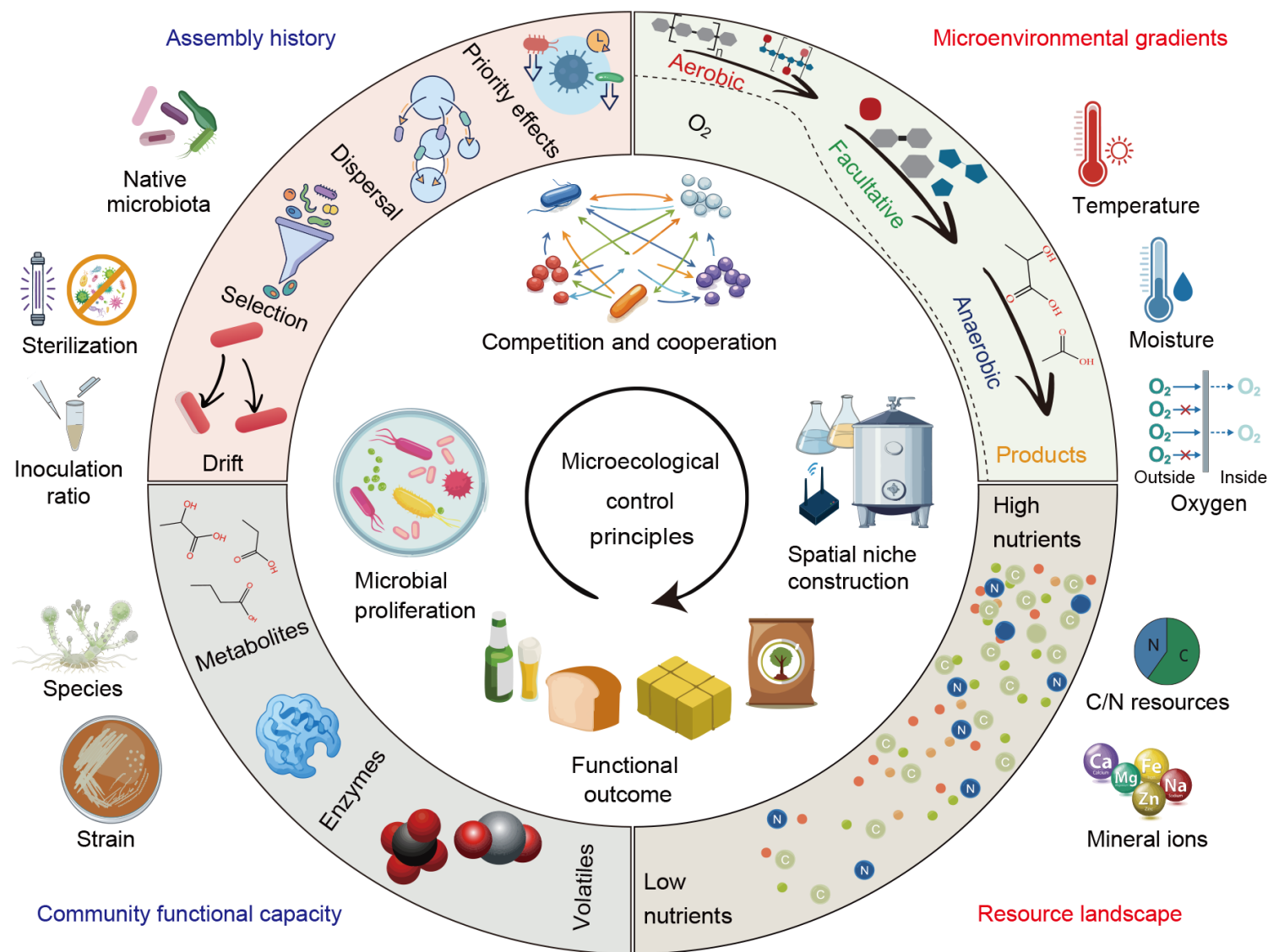


Figure 1C. Microecological regulation driven by community assembly and spatial niche construction



Cross-system omics integration and knowledge discovery

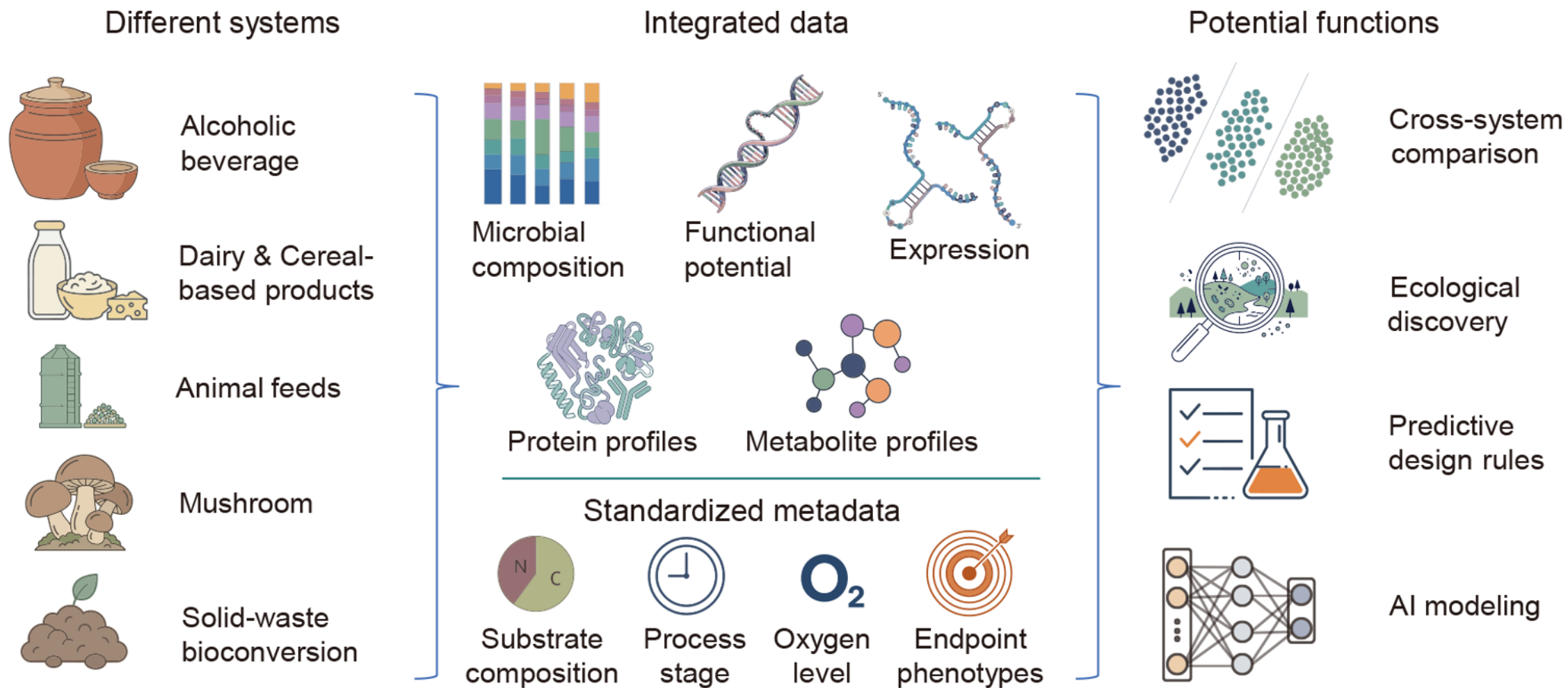


Figure 2A. From fragmented omics data to reusable fermentation knowledge



AI for fermentation microbiome research

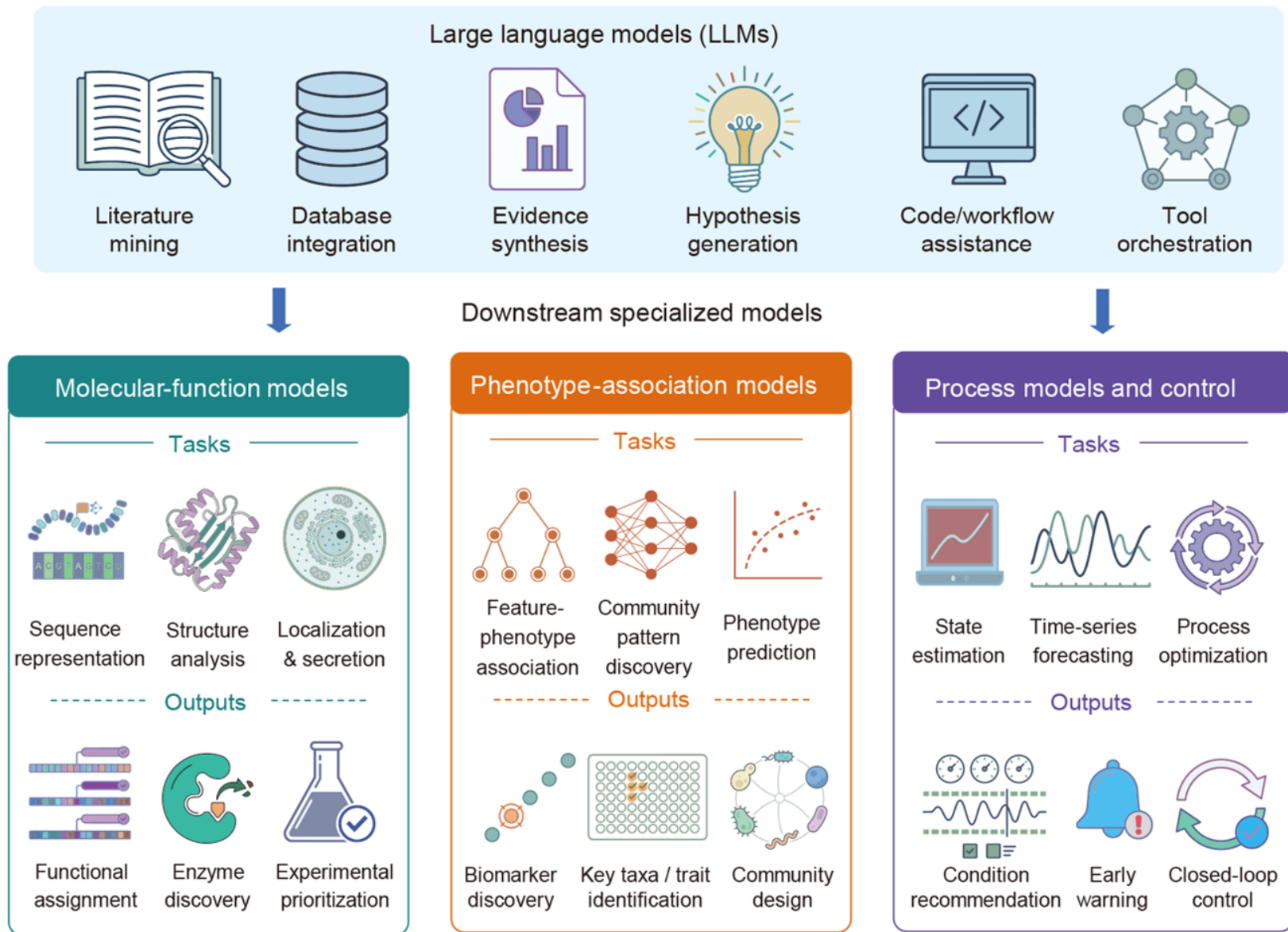


Figure 2B. A hierarchical AI framework integrating large language models and domain-specific models



Summary

- ❑ Spatial heterogeneity is a defining feature of high-solids fermentation and a major barrier to process optimization and scale-up, requiring a shift from transport-oriented thinking toward spatial niche design.
- ❑ Integrating multi-omics, process metadata, and phenotypic information across studies and fermentation systems will transform fragmented datasets into reusable knowledge for cross-system learning and predictive discovery.
- ❑ Multi-layer AI frameworks centered on large language models and domain-specific models will accelerate causal understanding, predictive design, and intelligent biomanufacturing of fermentation microbiomes.

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