**Highlights**

* Precision fermentation leverages synthetic biology and metabolic engineering for scalable and sustainable alternative protein production
* Embodied AI and multi-omics optimize microbial strain engineering and bioprocessing in precision fermentation
* Metabolic burden, substrate costs, and techno-economics remain challenges with “microbial cell factories” in precision fermentation
* The potential risk of nutrient inadequacies with cultured proteins may demand dietary interventions
* Infrastructure, regulatory clarity, and life cycle assessments are critical for fermentation-enabled alternative protein industry growth