Demonstration of Innovative Functional food production systems based on more sustainable value chains of marine and freshwater raw materials for conscientious EU consumers

NOVAFOODIES

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ITALIAN NATIONAL AGENCY FOR NEW TECHNOLOGIES, ENERGY AND SUSTAINABLE ECONOMIC DEVELOPMENT

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ALGAE-BASED INNOVATION FOR SUSTAINABLE PROTEIN DIVERSIFICATION: SENSORY QUALITY, NUTRITIONAL VALUE, AND APPLIED RESEARCH PERSPECTIVES

Rome, April 30, 2026

Funded by the European Union

This project has received funding from the European Union under Grant Agreement N° 101084180.

A Platform for Agro-Food Innovation

Protein Diversification

Highlighting resource efficiency and multi-product systems.

Natural Colorants

Replacing synthetic alternatives with sustainable bio-sources.

Bioactive Compounds

Delivering functional ingredients with high added value.

Inherently multi-product systems offering unmatched resource efficiency for functional ingredients.

The Deployment Paradox

High Innovation Potential

Low Industrial Implementation

The core problem is not the final product.
It is how we design, manage, and control the system.

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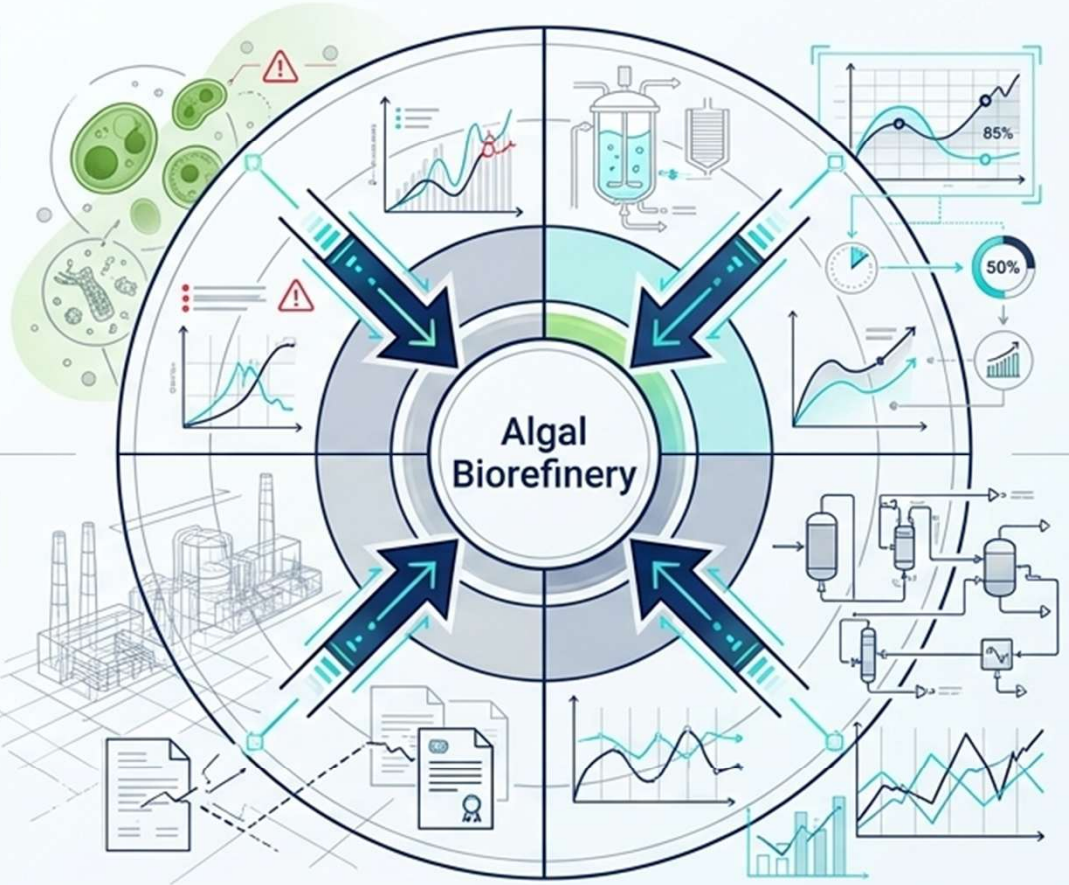
A System Constrained at Multiple Levels

Biological

Contamination risks and culture instability.

Physical

Cultivation inefficiencies and high harvesting costs



Systemic

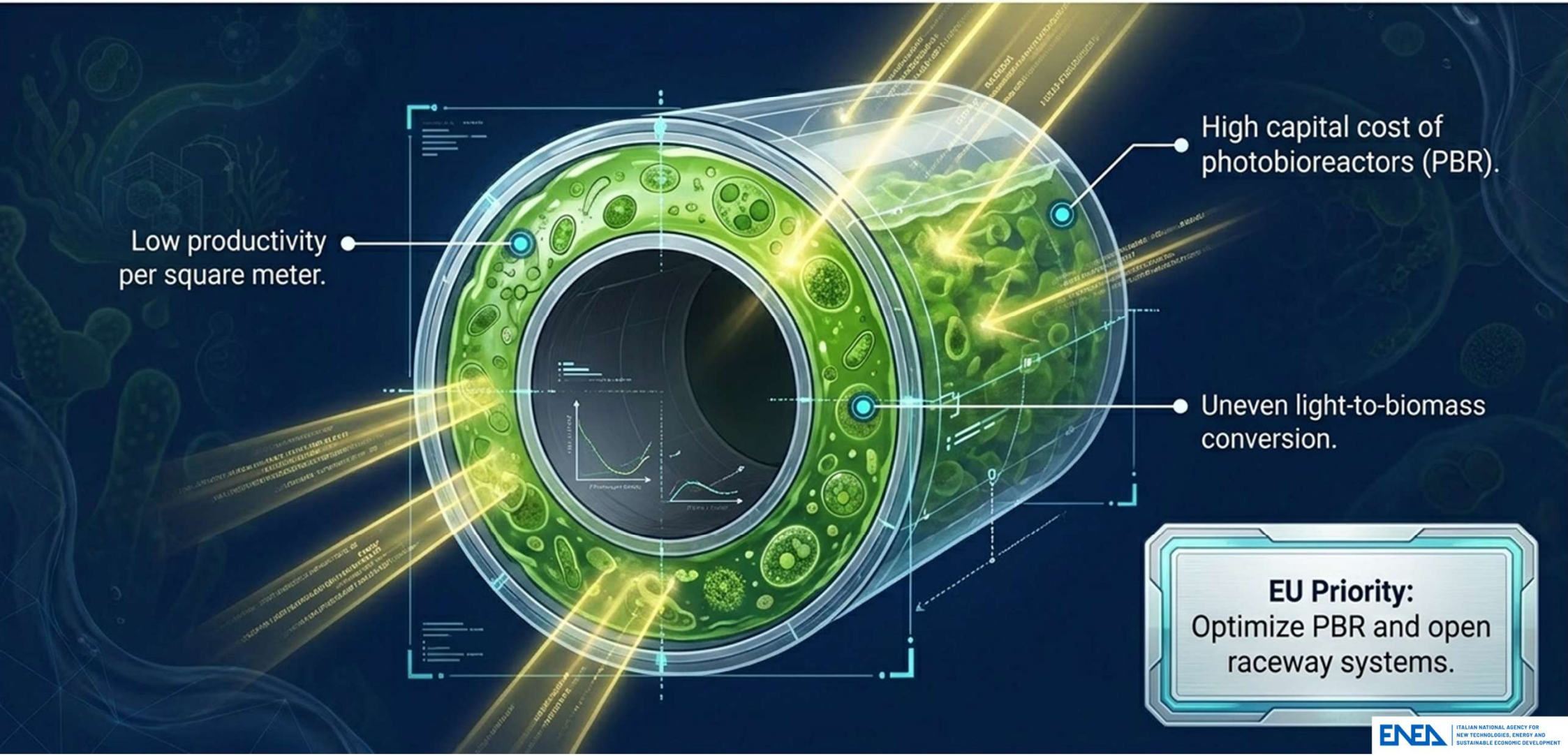
Limited industrial scale-up and regulatory fragmentation.

Economic

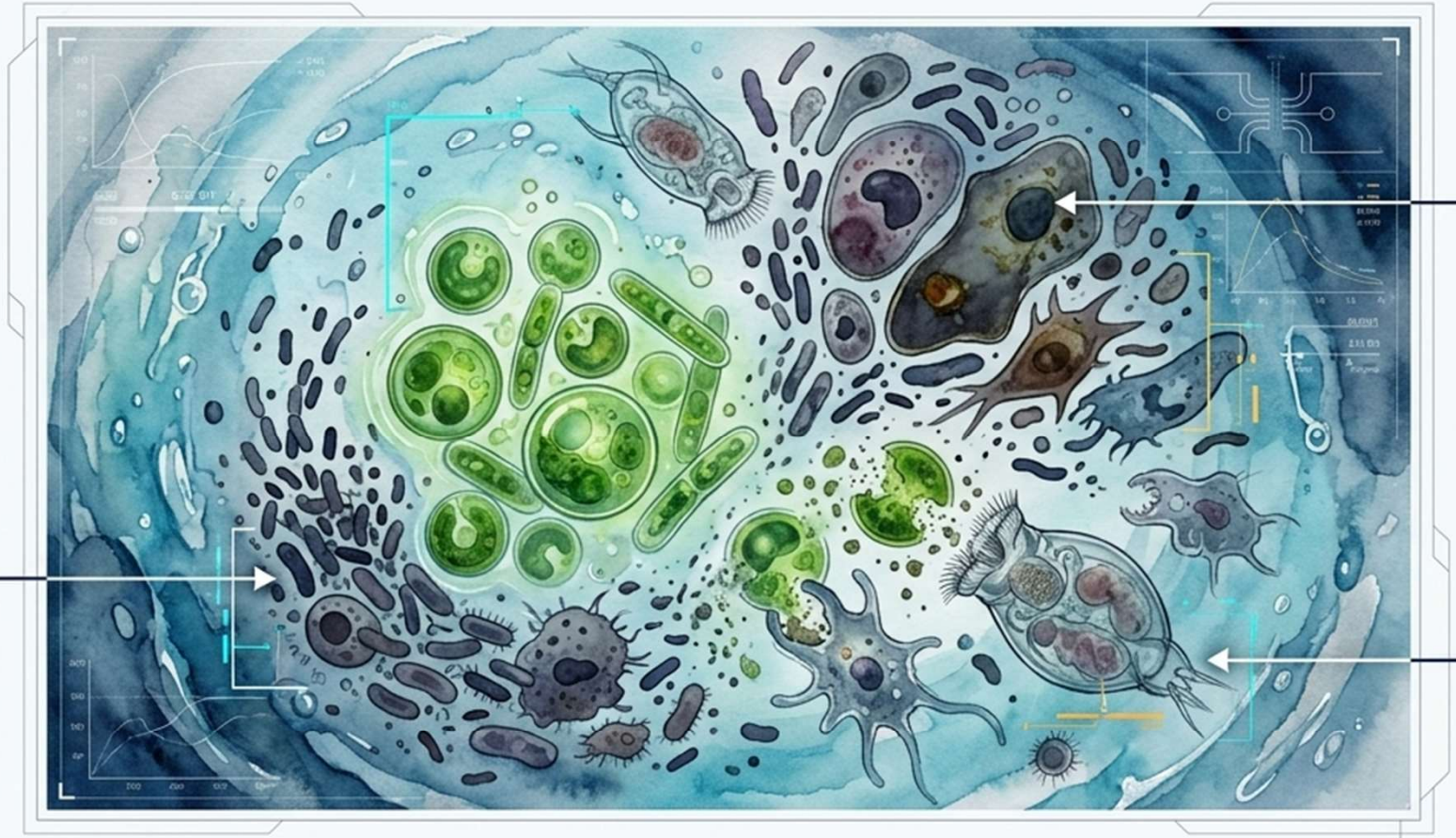
Multi-component downstream processing and market uncertainty

These bottlenecks are consistently identified across European reports and industrial analyses.
A single-point solution is insufficient.

Bottleneck I: The Cultivation Challenge

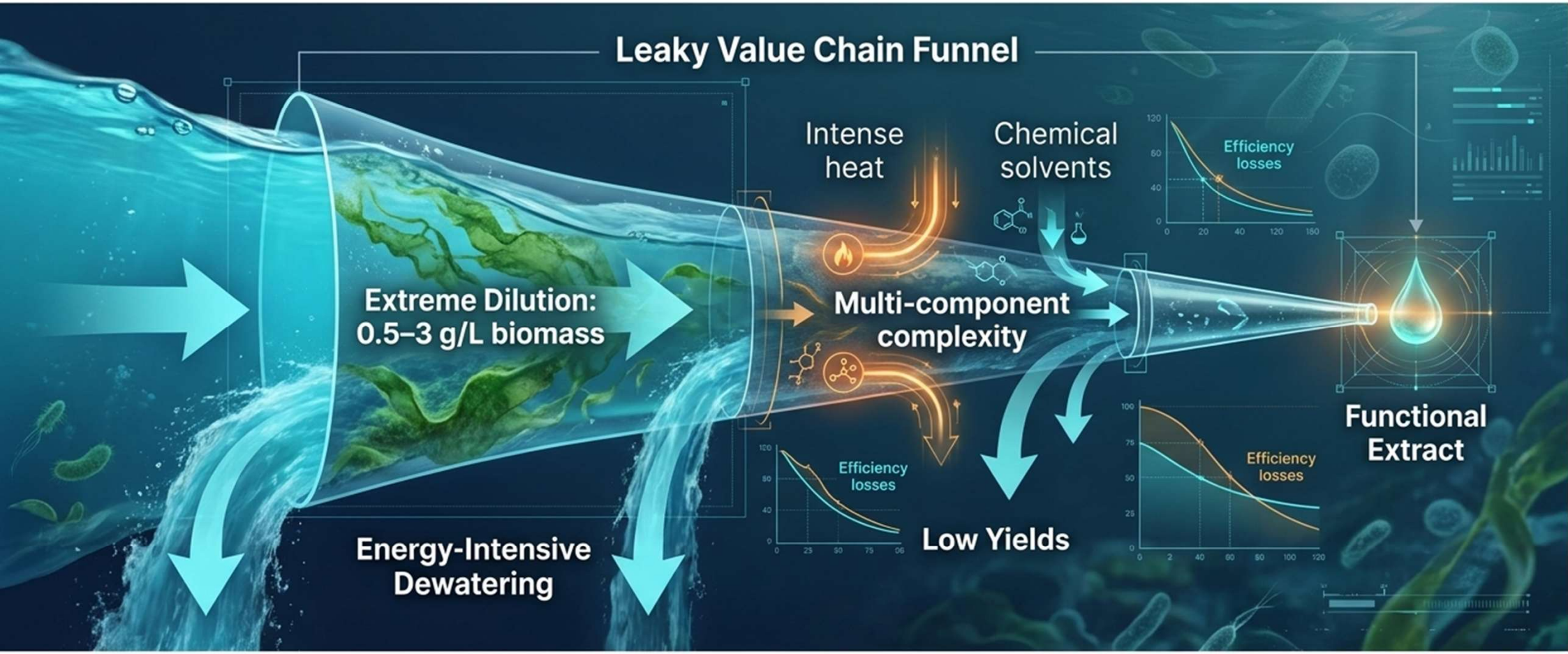


Bottleneck II: Contamination & Instability



Critical vulnerability in open systems where dynamic control over environmental parameters is severely limited.

Bottlenecks III & IV: Dilution & Downstream Complexity



Separating biomass from water and extracting complex mixtures dominates the economics of the entire process

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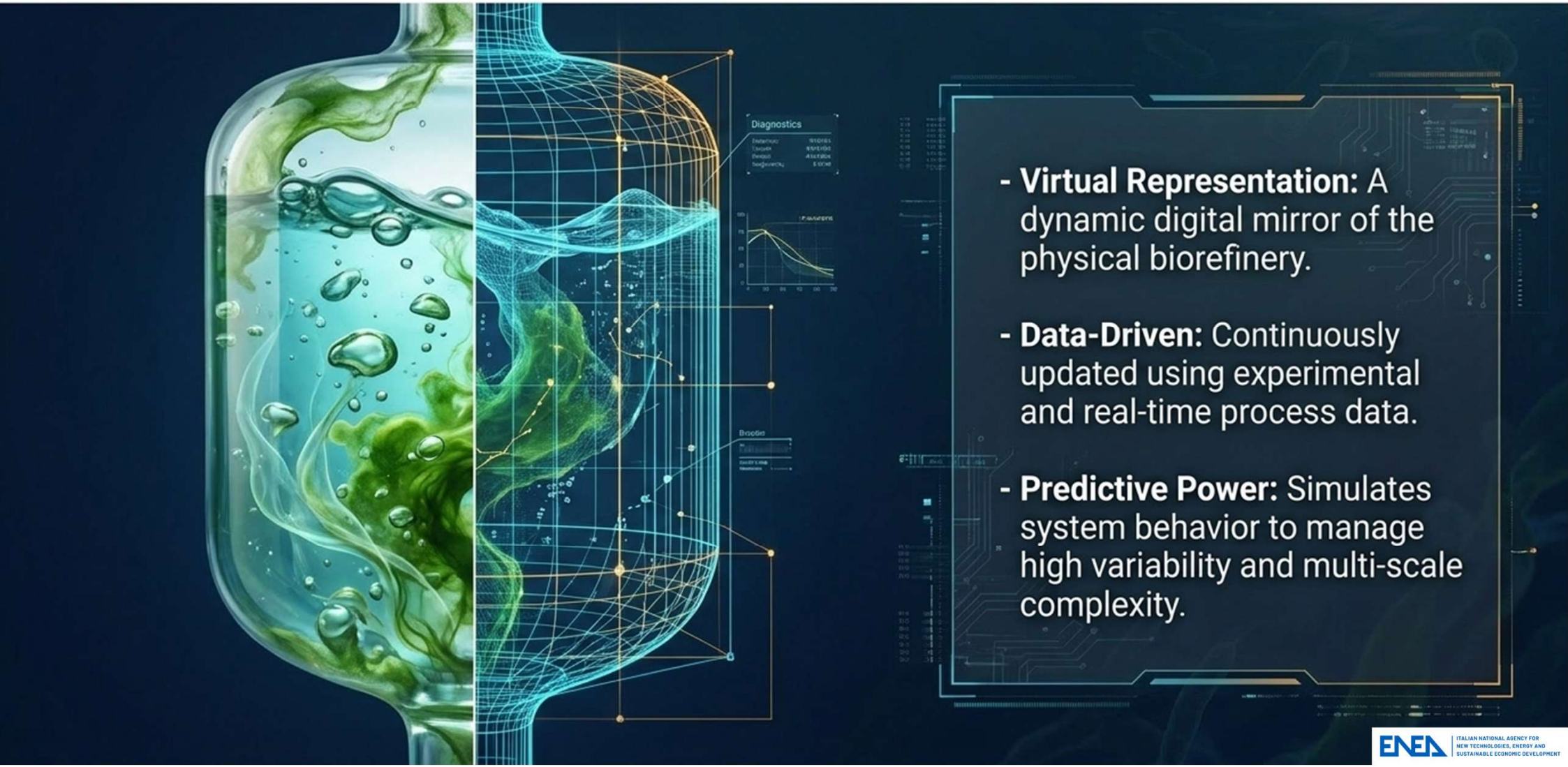
We are not limited by the potential of the biomass. We are limited by our capacity to control it.

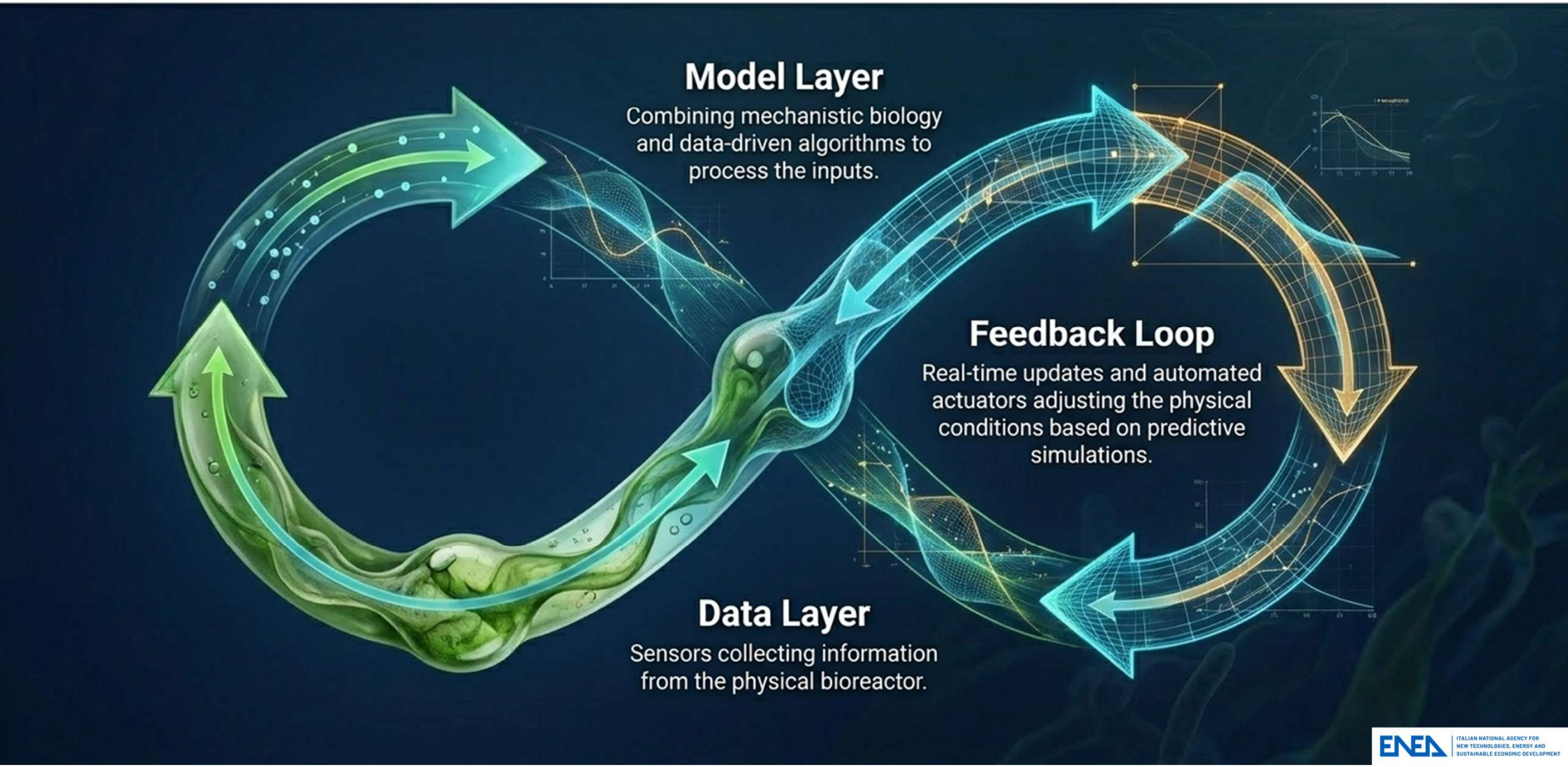
Moving from biological variability
to digital predictability.

Enter the Digital Twin



- **Virtual Representation:** A dynamic digital mirror of the physical biorefinery.
- **Data-Driven:** Continuously updated using experimental and real-time process data.
- **Predictive Power:** Simulates system behavior to manage high variability and multi-scale complexity.

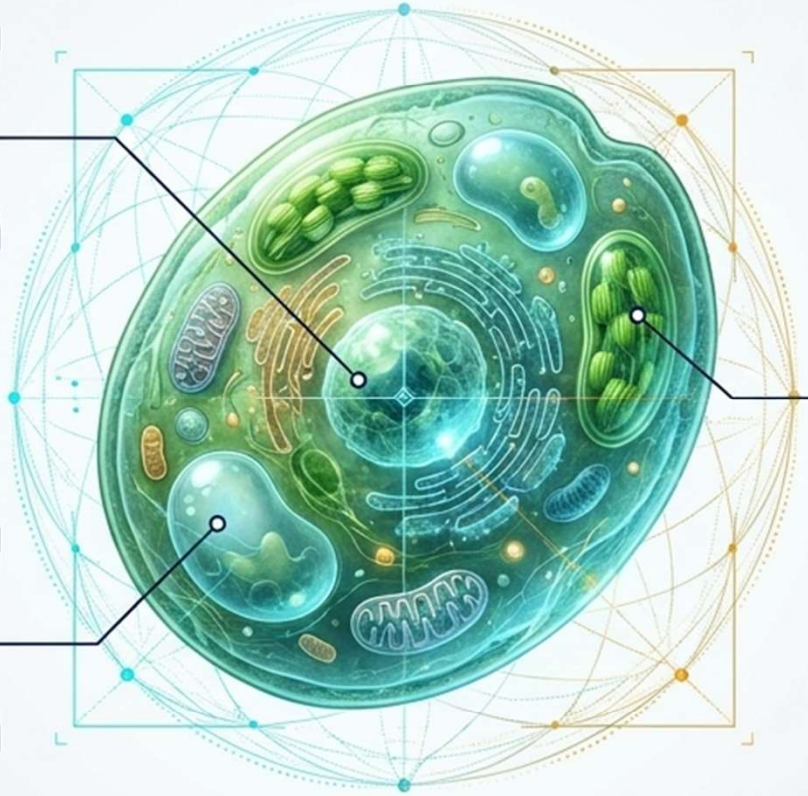
The Architecture of Predictive Control



The Core Unit: A Cellular Digital Twin

Metabolic State

Modeling internal energy and nutrient pathways.



Pigment Production

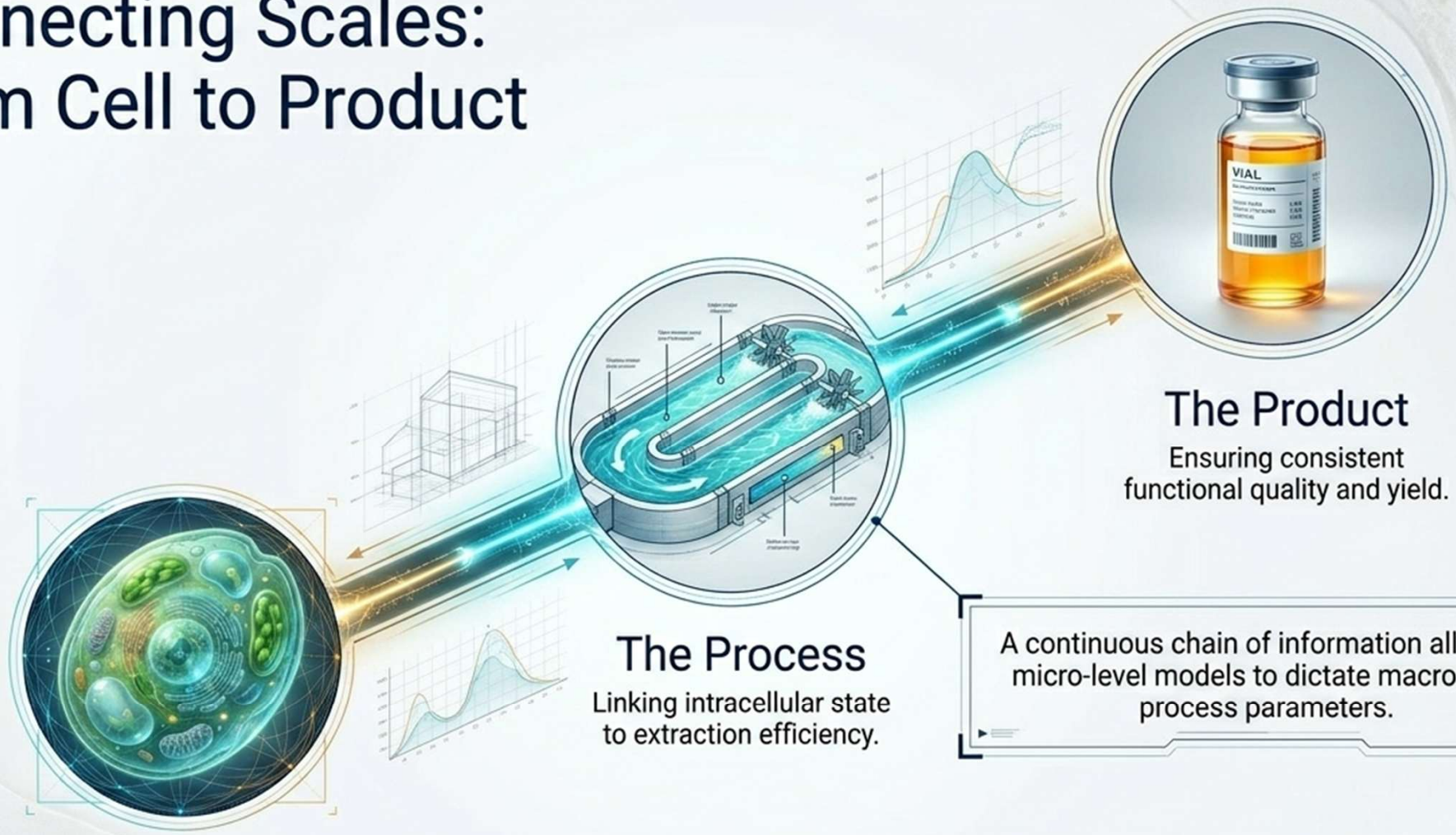
Tracking real-time synthesis of target molecules.

Stress Response

Simulating cellular reactions to environmental shifts.

Predicting final biomass composition *before* downstream processing begins.

Connecting Scales: From Cell to Product



The Product

Ensuring consistent functional quality and yield.

The Process

Linking intracellular state to extraction efficiency.

A continuous chain of information allowing micro-level models to dictate macro-level process parameters.

The Cell

The Paradigm Shift: Reactive vs. Predictive

	Traditional Approach (Reactive)	Digital Twin Approach (Predictive)
Process Control	Trial-and-error adjustments.	Simulated, anticipated optimal conditions.
Output Quality	Variable composition and unexpected degradation.	Standardized yields with preserved functionality.
Experimentation	Resource-intensive, high physical waste.	Reduced physical experimentation; optimized in the virtual space.
Scale-up	High risk of failure at larger scales.	De-risked through multi-scale predictive modeling.

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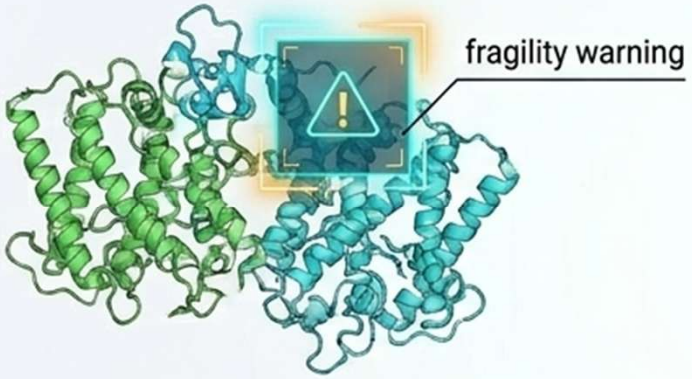
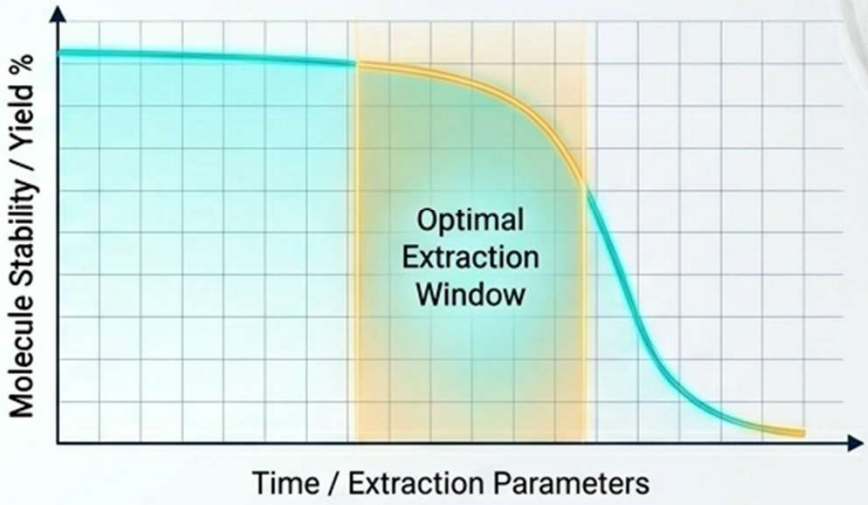
Validating the Model: The Phycoerythrin Case

The Challenge



A highly sensitive molecule. Stability is strictly dependent on volatile process conditions.

The DT Solution



- Predict exact degradation risks.
- Optimize physical extraction conditions.
- Simultaneously improve total yield and preserve functional quality.

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From Bottlenecks to Full Process Control

Algal biorefineries hold the key to agro-food innovation, but they are bottlenecked by biological variability and process inefficiency.

By adopting Digital Twin architectures—connecting the cell, the process, and the product—we transition from managing crises to engineering predictability.

Transforming systemic constraints into digital opportunities.

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Thank you very much for your attention!

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