CAROWIA

Fermenting the future of sustainable food and nutrition

Beyond technical feasibility: Precision fermentation-derived micronutrients for food system applications

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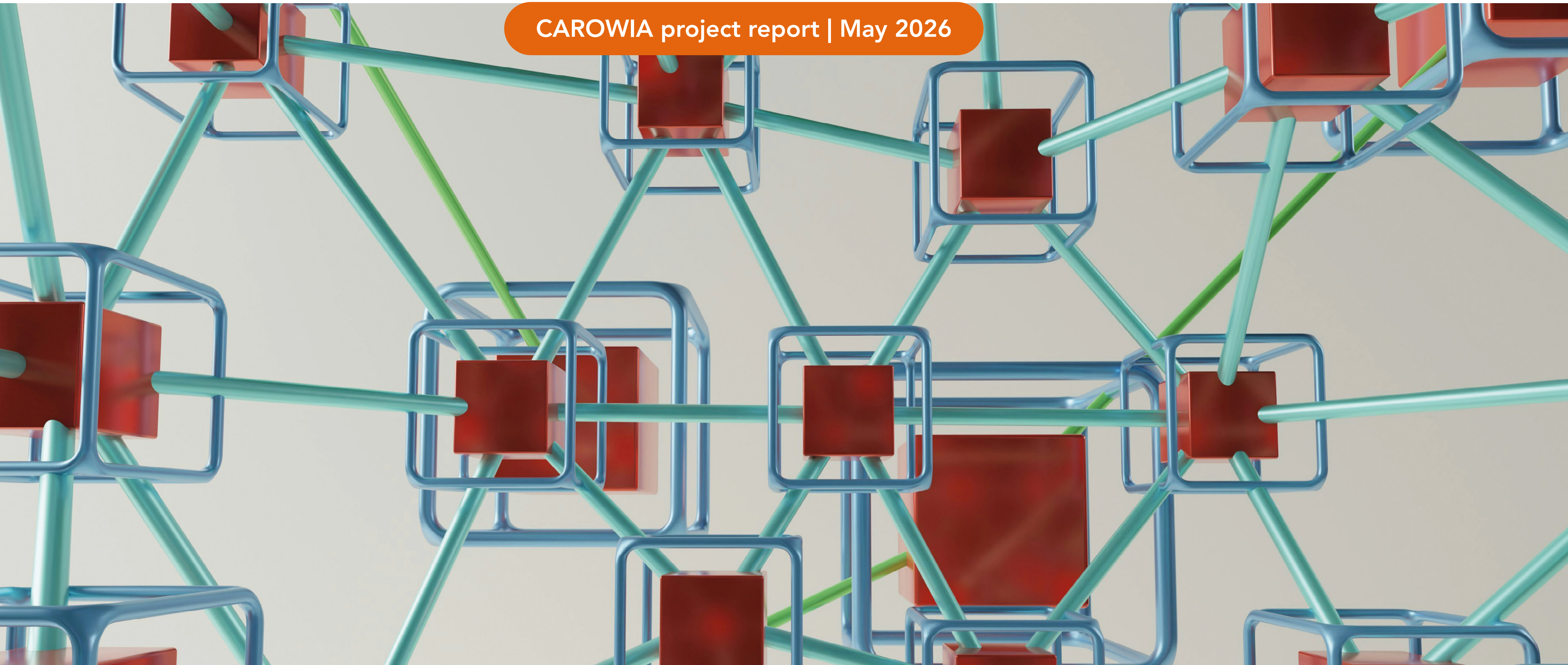


1. Introduction

Food systems today face multiple and interconnected challenges, including pressure on land and natural resources, vulnerability to environmental variability, and the need to deliver more resilient and sustainable nutritions in response to growing demand in the UK and globally. In this context, new production approaches are explored as potential solutions.

Precision fermentation is increasingly positioned as an innovative approach to producing micronutrients and functional ingredients, with the potential to reduce reliance on land-intensive agriculture and enable more flexible and resilient production pathways.[1] At its core, it refers to the **use of engineered microorganisms to produce specific target compounds through controlled biological processes**.

However, current discussions around the application of precision fermentation in the food system remain largely centred on technical feasibility, particularly whether these ingredients can be produced efficiently at scale, while the **real-world frictions involved in translating them into food system applications remain less explored**.

Funded by the UKRI Multidisciplinary Food System Commercialisation Catalyst Award, **CAROWIA (Unlocking the potential of precision fermentation for micronutrients)** is designed to bridge this gap. Using precision fermentation-derived ß-carotene as a concrete case, the project explores the techno-economic, market, regulatory, and social dynamics that shape **how precision fermentation-derived ingredients move beyond technical promise into viable food system applications**.

2. Precision fermentation for Food Systems: opportunities and challenges

Precision fermentation enables the targeted synthesis of defined molecules by introducing or optimising specific biosynthetic pathways within microbial hosts. Drawing on advances in synthetic biology, metabolic engineering, and bioprocess design, it allows microorganisms such as yeast, bacteria, or filamentous fungi to act as production platforms, converting feedstocks such as sugars or waste-derived substrates into high-value compounds with a high degree of specificity.[2]

Compared to conventional production methods of food ingredients, **precision fermentation offers more controlled and potentially less resource-intensive production, with the possibility of year-round supply and reduced exposure to environmental variability**. Importantly, it enables the production of ingredients that are chemically identical or functionally equivalent to those derived from plants, animals, or chemical synthesis, while offering advantages in consistency, scalability, and resource efficiency.[2]

At the same time, these opportunities must be understood in context. For example, established production systems always already exist for most micronutrients and ingredients, and markets are often highly cost-sensitive and functionally competitive. In many cases, **precision fermentation-derived micronutrients are not entering a blank space, but competing with existing ingredients and production methods that are already widely available and well understood**.[3]

Addressing these questions requires moving beyond technical performance in the lab alone, and considering how such ingredients perform economically at scale and how they interact with market dynamics, regulatory requirements, and consumer expectations within the food system.

3. Our approach: combining technology and system insight

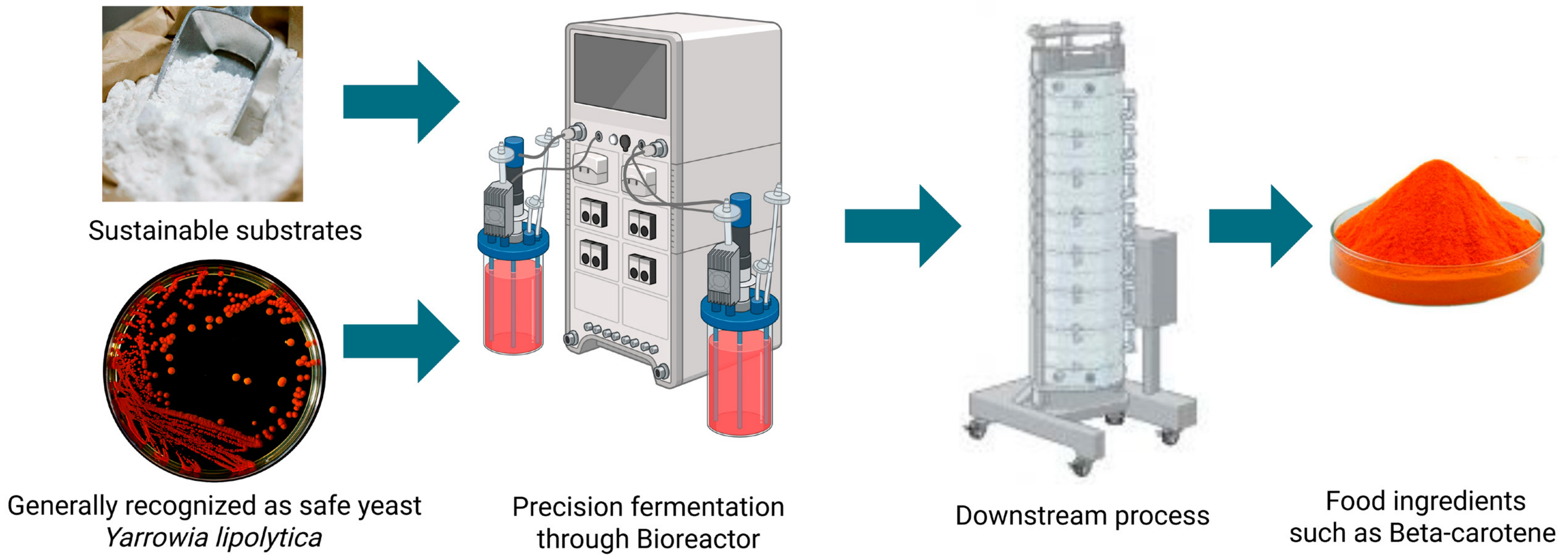
In the CAROWIA project, precision fermentation-derived ß-carotene was selected as a representative and analytically useful case due to its extensive applications across food, nutraceutical, cosmetic, and feed industries. **Widely used as a provitamin A and antioxidant to support vision, immune function, and overall health, ß-carotene can also serve as a platform compound for developing a broader portfolio of micronutrients**.[4]

ß-carotene is currently produced through established pathways, including chemical synthesis and extraction from plant or algal sources.[5] Growing demand, combined with increasing interest in naturally derived and sustainably produced ingredients, makes it a suitable proof-of-concept to explore whether precision fermentation-derived ingredients have the potential to earn a market position and the real-world frictions of this application.

To operationalise this approach, CAROWIA combines laboratory research, techno-economic analysis, and system-level investigation through a series of interconnected steps in six months:

- **Laboratory-scale experimentation** using engineered yeast in a 1 L bioreactor to establish proof-of-concept and generate initial performance data for precision fermentation-derived ß-carotene;
- **Techno-economic analysis (TEA)** to evaluate the technical performance and economic feasibility of precision fermentation-derived ß-carotene and identify the key cost drivers along the production chain based on the laboratory-scale experimentation;
- **Market and policy landscape analysis**, drawing on a commissioned report on the UK context for ß-carotene, to understand existing market structures, regulatory conditions, and competitive dynamics (3Keel);
- **Internal workshops** to co-develop potential commercialisation pathways, building on insights from the TEA and landscape analysis;
- **Multi-stakeholder workshop** to explore the real-world frictions that shape whether and how industry actors adopt precision fermentation-derived ingredients beyond techno-economic feasibility.

Figure 1: From yeast to products by precision fermentation



The figure illustrates the production pathway explored in the CAROWIA project, in which the GRAS yeast Yarrowia lipolytica converts sugar-based feedstocks into intracellular ß-carotene through controlled bioreactor fermentation. Following fermentation, downstream extraction and purification steps are required to recover ß-carotene as a food ingredient, which also represent important considerations in the techno-economic assessment.

4. Results

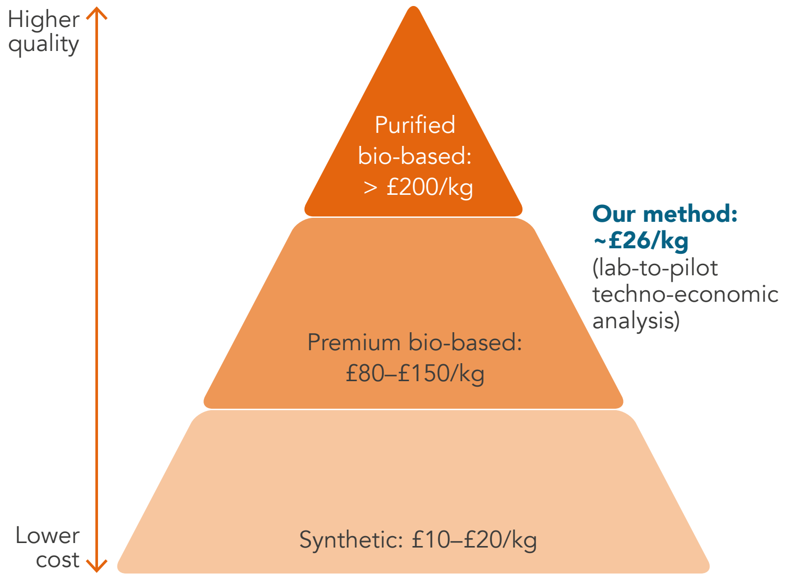
Our Laboratory-scale experimentation and TEA results suggested that **ß-carotene produced by precision fermentation using engineered yeast could reach a cost of approximately £26/kg** (Figure 2). This places it within the price range of natural, high quality alternatives derived from plants or algal sources currently available on the market, rather than competing with lower-cost synthetic products. This positioning suggests a potential role for precision fermentation-derived ß-carotene in segments that prioritise natural origin and product quality, rather than in price-driven commodity markets.

Feedstock costs are the main cost contributor (53.4%), further optimisation of processes and yeast strains to utilise agro industrial and food residues could both enhance sustainability and reduce overall production costs to support a circular economy, while also reducing the final product price.

Further reading

Commissioned 3Keel report on the UK market and policy landscape for ß-carotene

Figure 2: Indicative positioning of ß-carotene production pathways by cost and product value (data from CAROWIA TEA analysis and 3Keel report)



Systemic challenges

However, the translation of techno-economic feasibility into industrial adoption remains uncertain. Insights from internal and multi-stakeholder (involving over 20 participants across precision fermentation companies, policy and regulatory bodies including the Food Standards Agency, investors, and academia) workshops suggest that adoption is not constrained by a single bottleneck, but emerges from the interaction of multiple system-level factors, including:

Scale-up and techno-economic realities

While laboratory-scale feasibility can be demonstrated, scaling to industrial production introduces technical and economic uncertainties. Cost structures, infrastructure requirements, and access to capital and capabilities all influence the pace and distribution of scale-up.

Governance and distributed decision-making

Adoption pathways are shaped by a distributed decision system involving regulators, industry actors, investors, and consumers. Progress depends on alignment across these domains, with regulatory processes, market access, and investment decisions each introducing potential delays or uncertainties.

Consumer perception and trust

Early adoption is likely to occur in niche or premium segments, reflecting limited public familiarity with precision fermentation and competing narratives around naturalness and food processing. This highlights the importance of trust, framing, and communication in shaping uptake.

In summary, while precision fermentation-derived ingredients such as ß-carotene can achieve promising performance at the lab level, their translation into widespread food system applications remains constrained by fragmented scale-up pathways, uncertain alignment across regulatory and market systems, and limited mechanisms for distributing risk. Together, these tensions provide a structured lens for understanding the challenges of adoption in practice, and why promising technologies may remain confined to niche applications.

5. Implications and Future opportunities

Our findings from the CAROWIA project suggest that advancing precision fermentation-derived ingredients within food system applications is unlikely to be driven by individual ingredient-level optimisation alone, but will require integrated, system-level approaches. The following points emerged as particularly important considerations.

Enabling scale through new models

Current scale-up pathways favour well-capitalised actors able to absorb high upfront costs and technological uncertainty. This limits experimentation and slows diffusion across the sector. The findings point towards the importance of more shared or coordinated approaches to scaling, which could lower barriers to entry and enable broader participation.

Aligning regulation, investment, and innovation

The decision-making landscape identified in this study reveals misalignment between innovation timelines, regulatory approval processes, and investment horizons. Addressing this misalignment will be critical to reducing uncertainty and enabling more predictable pathways to adoption.

Engaging with perception and narratives

Consumer perception and trust emerged as key constraints on adoption, particularly where fermentation-derived ingredients are associated with unfamiliar or contested narratives. Improving uptake will require more coordinated approaches that address not only information gaps but also broader issues of trust and framing.

Rethinking value propositions

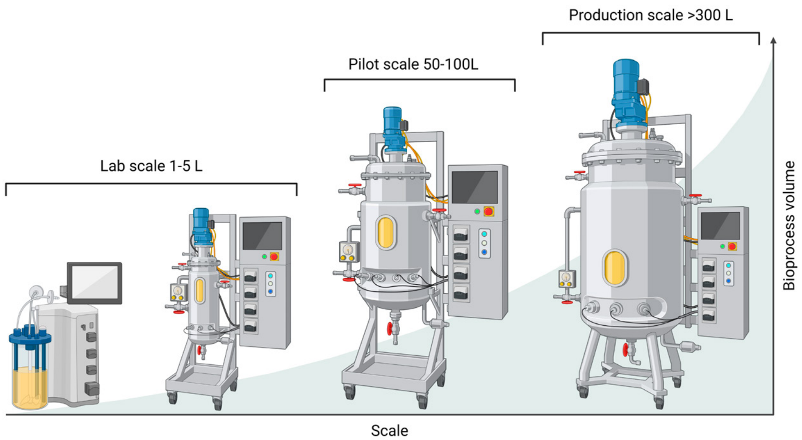
Finally, our findings suggest that future opportunities may lie beyond direct substitution of existing ingredients. Greater value may emerge through differentiated functionalities, targeted applications, or contributions to broader food system goals such as resilience and nutritional enhancement.

6. Next steps and collaboration opportunities

CAROWIA provides an initial step in understanding how precision fermentation-derived micronutrients translate into real-world food system applications, moving beyond technical feasibility to examine adoption pathways and system-level constraints. Based on these findings, we identify the following priorities for future work:

Scaling outlook

The next phase of the project will focus on generating further evidence to reduce uncertainty around scale-up and performance under more representative conditions. This includes advancing beyond laboratory-scale experimentation and refining techno-economic understanding through additional data and analysis. In parallel, this work will also provide a basis for exploring how insights from the ß-carotene case may translate to a broader portfolio of micronutrients within a platform-based approach.



Extending food system-level insight

Further work is also needed to deepen understanding of the system-level dynamics that shape adoption. While this project has explored key tensions through stakeholder engagement, there remains scope to broaden this work, particularly by engaging a wider range of actors across the food system. This includes further exploration of perspectives that have not yet been fully captured, such as those of consumers, as well as continued engagement with industry, policy, and investment communities.

Building on the tensions identified in this project, future research could further examine how these dynamics evolve across different contexts and applications, and how they influence the pathways through which precision fermentation-derived ingredients such as ß-carotene become integrated into food system applications.

We welcome opportunities to engage with partners across industry, policy, and academia to further explore these insights and identify collaborative pathways for scaling and system-level integration.

Figure 3: Scaling outlook

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Authors

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References

1 Waschulin, V. and Specht, E. 2018. Cellular agriculture: An extension of common production methods for food. Forest, Belgium: GFI Europe.

2 Graham, A.E. and Ledesma-Amaro, R. 2023. The microbial food revolution. *Nature Communications*, 14.1: 2231. doi: 10.1038/s41467-023-37891-1

3 The Good Food Institute and Arthur D. Little Consultancy, 2025. Pathfinding towards precision fermentation viability. Forest, Belgium: GFI Europe.

4 Larroude, M., Celinska, E., Back, A., Thomas, S., Nicaud, J-M. and Ledesma-Amaro, R. 2018. A synthetic biology approach to transform Yarrowia lipolytica into a competitive biotechnological producer of ß-carotene. *Biotechnology and bioengineering*: 115.2: 464-472. doi: 10.1002/bit.26473

5 Martin, J., Mariam, S. and Jones, K. 2026. Market & policy landscape report for beta-carotene. 3Keel for the CAROWIA project.

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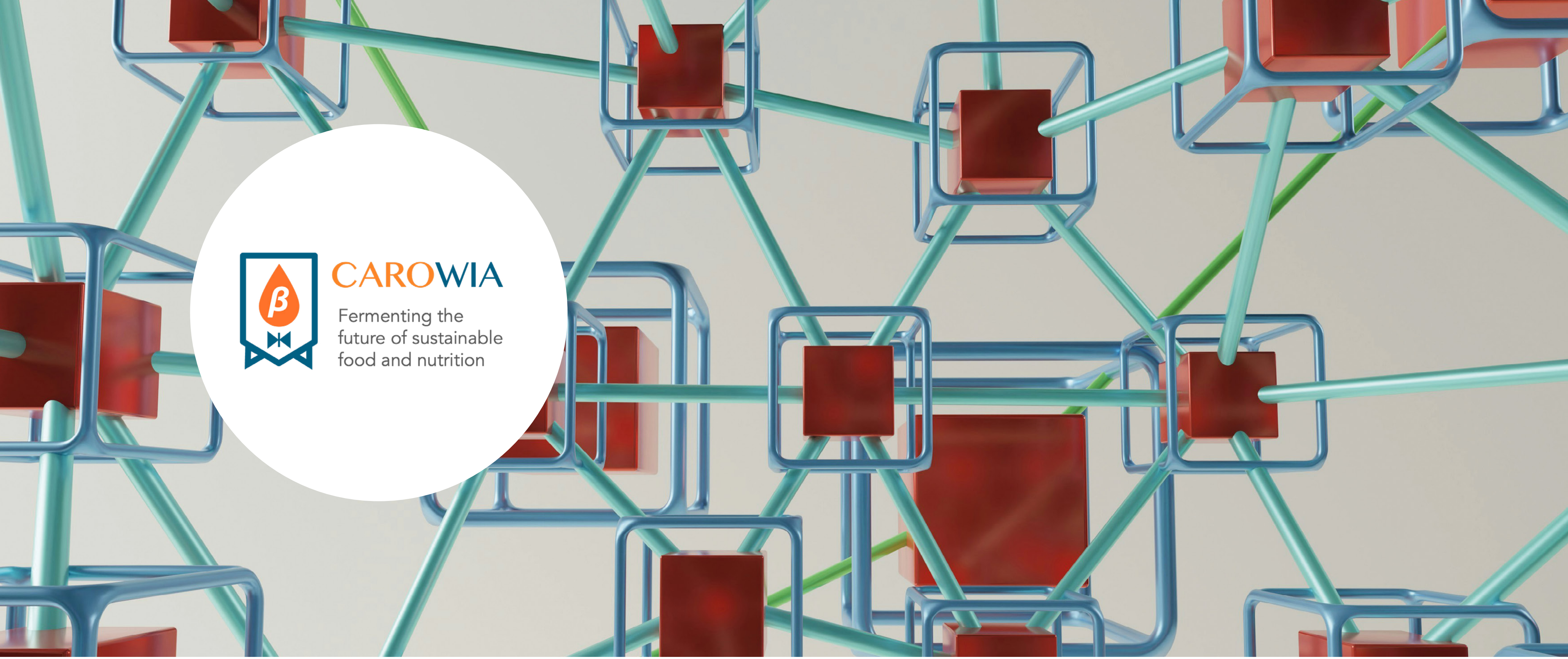

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Co-led by the University of Oxford and Imperial College London, CAROWIA explores how precision fermentation-derived micronutrients can move from technical promise into real-world food system applications.