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Special issue article

Evolution of innovation and production supply chains: the case of microalgae-based β-carotene

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Abstract

Establishing new bio-based sectors requires effective implementation of innovation and production supply chains, often competing with established synthetic technologies. Our analytical model conceptualizes the competition between an incumbent industry and a competitive fringe, each producing differentiated products. Although motivated by the β-carotene case, the model is versatile and applicable to other contexts involving novel products entering markets dominated by established technologies. Developed by university researchers and commercialized by start-ups, natural β-carotene was eventually integrated into major synthetic corporations. Initially niche and costly, it gained market competitiveness through innovation and expanded applications, driving technological advancements and significantly benefiting the broader algae-based industry.

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1. Introduction

The transition to a bioeconomy is increasingly recognized as a vital strategy for achieving sustainable development in the face of global environmental challenges and the depletion of non-renewable resources (Zilberman et al., 2018). The bioeconomy, which leverages biological resources and processes to produce goods and services, promises to reduce environmental impacts while fostering economic growth (Kardung, et al., 2021). It extends beyond traditional agriculture by incorporating biotechnology, renewable energy, waste valorization, and innovative industrial processes. Within this emerging sector, microalgae have garnered significant attention due to their potential to serve as sustainable sources of high-value chemicals, such as β-carotene (Ben Amotz, 1995; Fernandez et al., 2021). β-carotene, a carotenoid with applications in food, cosmetics, and pharmaceuticals, represents a critical case for understanding the dynamics of innovation and production supply chains in the bioeconomy.

Microalgae-based β-carotene production exemplifies the complexities and opportunities inherent in the bioeconomy. Microalgae-derived β-carotene was developed as a natural alternative to synthetic β-carotene, offering documented advantages in health outcomes and consumer-perceived quality, as consistently supported by academic studies (Burri, 1997). Unlike traditional agriculture, microalgae cultivation does not compete for arable land or freshwater resources, making it a more sustainable option (Hochman and Palatnik, 2022). Moreover, microalgae exhibit faster growth rates than most terrestrial plants, enabling the production of large biomass quantities in relatively short periods (Borowitzka and Vonshak, 2017). However, the economic viability of microalgae-derived products hinges on the ability to innovate and scale production efficiently (Borowitzka M., 2016). This paper investigates the evolution of the microalgae-based β-carotene industry through the lens of innovation and production supply chains, highlighting how these processes interact to drive industry growth and competitiveness.

Central to the development of bio-based industries is the interplay between the Innovation Supply Chain (ISC) and the Production Supply Chain (PSC) (Zilberman et al., 2022). The ISC encompasses the journey from basic research and development to commercialization, focusing on creating and refining new products and technologies. In the case of microalgae-based β-carotene, the ISC includes the initial discovery that *Dunaliella salina* thrives in saline environments (Ginzburg M., 1988), followed by the discovery that this species of microalgae is a rich source of β-carotene (Ben-Amotz, Shaish and Avron, 1991). The simultaneous development of lab-to-market initiatives in freshwater-scarce regions of Australia, Israel, and California led to the development of efficient cultivation methods (Ward, 2014), and technological advancements in extraction and processing made large-scale production possible.

The PSC, on the other hand, deals with the processes required to manufacture and deliver these innovations to the market (Zilberman et al., 2022). This includes sourcing raw materials, production, processing, and distribution. For microalgae-based β-carotene, the PSC involves the cultivation of microalgae in ponds or photobioreactors, the extraction of β-carotene, the impact of regulation, demand by early adopters that shapes the product, and the supply chain logistics that bring the final product to consumers. The success of the PSC in this industry depends on achieving cost efficiencies, maintaining quality control, and scaling production to meet market demand.

The dynamic relationship between the ISC and PSC is crucial for the success of bio-based industries. Innovations developed in the ISC directly impact the efficiency and scalability of the PSC, while challenges encountered in the PSC can drive further innovation within the ISC. This feedback loop is particularly evident in the microalgae-based β-carotene industry, where continuous advancements in cultivation technology and process optimization have enabled the industry to overcome significant barriers to entry, such as high initial costs and variation of yields under uncertain production conditions.

This paper contributes to the existing literature in several ways. First, it offers a conceptual framework that extends the static model by Zilberman et al. (2022) to a multi-scenario analysis of bio-economy products introduced into markets dominated by synthetic alternatives in anticipation of higher premiums. Inspired by the case of algae-based β-carotene, the framework can also be applied to other cases, such as biofuels and green hydrogen entering the energy market, or bioplastics and biostimulants to replace chemicals and fertilizers. The framework is general and applicable to describe the behavior of any start-up that aims to enter the existing market with a product characterized by better features that the entrepreneur expects would attract buyers with higher demand and willingness to pay (WTP). The model explores how natural products compete with synthetic ones, accounting for consumer preferences, pricing strategies, and market dynamics. Second, it applies the theoretical framework to a real-world example of the microalgae-based β-carotene industry, demonstrating the critical factors in the successful development of bio-based industries. Finally, the paper discusses the broader implications of these findings for policymakers and industry stakeholders, emphasizing the lessons learned in the broader context of the bioeconomy.

In the following sections, we first present a conceptual framework with a particular emphasis on bioeconomy, innovation supply chains, and production supply chains. Next, an analytical model is developed to specifically address the critical stage in the production supply chain when a bio-based alternative enters a market dominated by the synthetic-based product, exploring the dynamics under varying market conditions. Subsequently, we apply the theoretical framework to the case study of microalgae-based β-carotene, systematically tracing the evolution of this industry from its inception to its current market status. The subsequent discussion explicitly connects the empirical findings to the theoretical concepts of the bioeconomy, highlighting the main insights and practical lessons emerging from the analysis. Finally, the paper concludes by outlining implications for both future research agendas and policy development.

2. Conceptual framework

The global shift towards a bioeconomy represents a critical transition in addressing the environmental and economic challenges posed by reliance on the chemical processing of depletable resources (Zilberman, 2014). This transition is driven by the need to develop sustainable production systems that utilize biological resources, reducing the environmental footprint while supporting economic growth (Wesseler and von Braun, 2017). Central to the evolution of the bioeconomy is the development of effective innovation and production supply chains. These supply chains are key to facilitating the adoption of renewables-based industries by enabling the efficient translation of scientific discoveries into marketable products and by ensuring that these goods are produced and delivered in a cost-effective manner (Zilberman et al., 2022). This section introduces a conceptual framework where the higher quality natural-based product is introduced in the market of the incumbent synthetic alternative. The model then expanded to explore the primary concepts behind the growth of the bioeconomy: demand creation, market structure, and learning by research and doing in multiple stages of innovation and production supply chains

2.1. Innovation and production supply chains

The development of most biological products involves complex, multistage supply chains. For instance, corn or sugarcane is cultivated to extract sugars, which are then processed to produce biofuels and bioplastics (Brodin et al., 2017). Similarly, algae cultivation is the first stage for producing sugars and proteins for fish and meat supplements (Palatnik et al., 2023). Despite the complexity of these supply chains, much of the existing bioeconomics literature has primarily focused on specific segments of the bio-based system (Mujtaba et al., 2023). One significant area of emphasis is the economic assessment of individual bio-based projects (Palatnik et al., 2023; Golberg, 2020; NAS, 2020; Wesseler and von Braun, 2017). Another critical focus is the economics of bioeconomy production at the farm level (Raimondo et al., 2021; Nicholson et al., 2023). While these studies offer valuable insights, they often do not provide a holistic view of the entire supply chain.

The evolution of bioeconomy industries, particularly in emerging sectors such as microalgae-based β-carotene production, can be effectively analyzed through the lens of the ISC and Production Supply Chain (PSC) frameworks (Zilberman et al., 2022). These two interrelated concepts offer a robust framework for understanding the processes of transforming an initial product concept into a market-ready reality.

Innovation supply chain	Stages	Discovery/ innovation	Development	Upscaling
	Mechanisms	• Relentless • Recombinant • Education Industrial Complex		
and planning under uncertainty Demand assessment				
Product supply chain	Stages	Upstream: Feedstock	Midstream: Processing	Downstream: Distribution
	Mechanisms/ Endogenous Market Structure	• Leading firm • Free markets • Vertical integration • Contracting		

Fig. 1. Innovation and production supply chains.

The ISC refers to the process of transforming scientific discoveries into marketable products. It begins with the stage of basic research and innovation, which leads to the discovery of new materials, processes, or technologies (Figure 1). Next is the development phase, where these discoveries are refined and tested for practical applications. Once a viable product or process is identified, the next stage involves upscaling, which includes pilot production, further optimization, and preparation for commercialization. Finally, the product is introduced to the market, where it undergoes further refinement based on consumer feedback and market demands.

Innovation is fundamental to ensuring that the bioeconomy can produce more with fewer inputs (Brooks, 1994). In the case of the microalgae-based β-carotene industry, the ISC began with the discovery of *Dunaliella salina*'s high yields in hypersaline waters. This initial research, conducted in the 1960s and 1970s, laid the groundwork for further development, including the optimization of cultivation methods and the search for high-value applications that led to the discovery of the ability to produce high levels of β-carotene and the refinement of β-carotene extraction processes. As the industry matured, these innovations were scaled up, leading to the commercialization of natural β-carotene products for use in food, cosmetics, and pharmaceuticals.

The ISC is characterized by the mechanisms of a continuous feedback loop between research and market needs. Innovations are relentlessly driven by demand fluctuations and regulation. As new products are introduced, they prompt further research and development to enhance performance, lower costs, and broaden applications. This process is often recombinant, incorporating relevant technologies from other fields, and the innovations developed often lay the foundation for future novel products. A vital feature of the ISC is the industrial-education complex, which fosters collaboration between research institutions and industry (Rosenberg, 2010). Research conducted in university labs is applied to develop specific technologies and products with the potential to become profitable alternatives to existing solutions, ensuring a dynamic flow of knowledge and innovation between academia and industry. Entrepreneurs constantly update their expectations about demand and adoption patterns.

The PSC, on the other hand, encompasses the series of stages required to manufacture and deliver products to consumers (Figure 1). It starts from the upstream production of feedstock and the procurement of raw materials. It is followed by midstream processing, manufacturing, distribution, and ultimately downstream marketing. This stage involves the logistics of delivering the product to consumers, managing inventory, and promoting the product to target markets.

Endogenous market structure and market mechanisms can significantly influence the evolution and behavior of PSC. Initially, the innovator may enjoy a monopoly, but the entry of competitors over time can alter the market dynamics, transforming it into an oligopoly or monopolistic competition. Competing firms may offer differentiated products, yet these alternatives often retain a high degree of substitutability with the original innovation.

Microalgae-based β-carotene was developed as a natural alternative to synthetic β-carotene. The bio-based nature of this product has been perceived as advantageous, supported by several studies documenting advantages in outcomes between synthetic and natural variants (Ben-Amotz and Avron, 1980). The PSC of natural β-carotene includes the cultivation of *Dunaliella salina* in saline lakes, ponds, and controlled environments to ensure optimal growth conditions and cost efficiency. Midstream activities involve harvesting the microalgae, extracting the β-carotene, and formulating the final product in powder or oil form, with varying concentrations of β-carotene. The initial producers of the industry were vertically integrated, managing both the cultivation of feedstock and the processing into final products with different β-carotene concentrations. Institutions and policies played a crucial role in shaping the risks for profitable production, or reducing transaction costs through public investments in infrastructure. For instance, until 2009, legislation prohibited the use of Dunaliella salina-based β-carotene in food products in the U.S. (Federal Ministry of Food and Agriculture, 2023).

Zilberman et al. (2022) highlight the feedback relationship between ISC and PSC, arguing that successful innovation often leads to efficient production processes and vice versa, creating a symbiotic relationship that drives economic growth and market expansion. For example, advancements in cultivation technology can lead to higher yields of microalgae, reducing costs and improving production's scalability. Conversely, the challenges encountered in the PSC—such as the need for cost-effective harvesting methods, product characteristics that meet regulation or demand requirements, or the logistical complexities of distribution—can drive further innovation within the ISC.

The following sub-section presents the analytical model that addresses the impact of market conditions within the PSC (Figure 1) when a novel bio-based alternative to the synthetic-based product is introduced. Building upon the models by Zilberman et al. (2022) and Sobolevsky, Moschini and Lapan (2005), the analytical model helps understand the dynamics between synthetic and bio-based producers, exploring their mutual impacts on profitability and how their interactions shape the evolving structure of both markets.

This framework is inspired by the case of algae-based β-carotene, which entered a market where synthetic β-carotene was already well-established, and entrepreneurs anticipated a premium for the natural alternative. However, the analytical model is versatile and can be applied to any context where a novel alternative enters a market of established technology, such as introducing bio-fuels into the fossil fuel market, organic produce in conventional agriculture, and even generic drugs competing with brand-name pharmaceuticals. In each case, the model explores how natural or bio-based products compete alongside synthetic counterparts, considering consumer preferences, pricing strategies, and market dynamics.

2.2. The analytical model

The analytical model provides a detailed snapshot of the upstream market, focusing specifically on the interplay between synthetic and organic feed-stocks. While zooming in on the upstream market, we have developed an analytical model to better understand the dynamics within the natural beta-carotene industry across the historical timeframe examined, from the 1960s to the 2020s. The model assumes two sectors: synthetic and natural beta-carotene producers, with their products being imperfect substitutes. To capture varying market conditions, we consider six scenarios indexed by $i = 0, \ldots 5$. The inverse demand for synthetic beta-carotene in scenario i is denoted as $P_i^s(x_i^s, x_i^n)$ which represents the price consumers are willing to pay for synthetic beta-carotene, given x_i^s–the quantity of the synthetic product consumed and x_i^n—the quantity of the natural product consumed. The demand functions exhibit standard properties of downward-sloping demand ($\frac{\partial P_i^n}{\partial x_1^n} \leq 0$, $\frac{\partial P_i^s}{\partial x_1^s} \leq 0$). Because $x_i^n$and x_i^s are substitutes, an increase in the consumption of the natural productx_i^n reduces the willingness to pay for the synthetic product ($\frac{\partial P_i^s}{\partial x_i^n} \leq 0$), causing the demand curve for the synthetic product to shift downward and to the left. Similarly, the inverse demand for the natural product is given by $P_i^n(x_i^n, x_i^s)$ which declines with an increase in x_i^n *or* x_i^s: $\frac{\partial P_i^n}{\partial x_i^n} \leq 0$ *and* $\frac{\partial P_i^n}{\partial x_i^s} \leq 0$.

The following case study offers insight into the properties of the inverse demand functions for synthetic and natural beta-carotene. In beta-carotene and similar supply chains, the established (synthetic) product of the incumbent technology often benefits from a more extensive dealer network, amplifying the demand. This pattern is consistent with observations across industries, where first-mover advantages or long-standing market presence result in stronger distribution networks and greater consumer accessibility (e.g. by dealers). For instance, branded drugs frequently dominate market reach in the pharmaceutical industry due to well-established distribution systems (Jaberidoost, Abdollahiasl and Dinarvand, 2013). Similarly, a significant portion of supply chain development revolves around building robust marketing and distribution networks. This is particularly evident in the organic food sector, where producers rely on such networks to differentiate and market their products effectively (Raynolds, 2004).

Accordingly, we assume that there exists a segment of consumers with a strong preference for natural products, reflected in their higher willingness to pay for these products relative to synthetic alternatives.

Let $C_i^n(x_i^n)$ and $C_i^s(x_i^s)$ represent the total production costs for natural and synthetic products, respectively, under scenario i (i.e. $\frac{\partial C}{\partial x} = MC$). The marginal cost, MC, for both products, is positive and increasing. The marginal cost of the natural product $MC_i^n(x_i^n)$ is higher than that of the synthetic product $MC_i^s(x_i^s)$. The gap between the marginal costs increases with production because the incumbent synthetic product has a larger market and a longer history that enables learning by doing. Formally, $MC_i^n(x_i^n) \geq 0$ and $MC_i^s(x_i^s) \geq 0$, with $\frac{\partial MC_i^n}{\partial x_i^n} \geq 0$ and $\frac{\partial MC_i^s}{\partial x_i^s} \geq 0$, and $\frac{\partial [MC_i^n(x) - MC_i^s(x)]}{\partial x} \geq 0$. These assumptions form the basis for deriving the subsequent results.

The scenarios:

Scenario $i = 0$: This baseline represents the competitive market equilibrium before the natural product becomes available, with the objective function specified in equation (1).

$$\max_{x_0^s} \{P_0^s(x_0^s, 0)x_0^s - C_0^s(x_0^s)\} \tag{1}$$

Under competition, output is determined where the marginal cost of the synthetic product is equal to the inverse demand, i. e. the price of the synthetic product. In particular,

$$P_0^s(x_0^s, 0) = p_0^s = MC_0^s(x_0^s)$$

Scenario $i = 1$: This scenario represents competition when both natural (3) and synthetic (2) products are available.

$$\max_{x_1^s} \{P_1^s(x_1^s, x_1^n)x_1^s - C_1^s(x_1^s)\} \tag{2}$$

$$\max_{x_1^n} \{P_1^n(x_1^n, x_1^s)x_1^n - C_1^n(x_1^n)\} \tag{3}$$

In this case, the equilibrium output of the natural and synthetic products will be at x_1^n and x_1^s, respectively. In this context, the lowercase 'p' represents prices, while the uppercase '*P*' denotes the inverse demand function. Market equilibrium occurs when supply meets demand in both markets.

$$P_i^s(x_1^s, x_1^n) = p_1^s = MC_i^s(x_1^s)$$

$$P_i^n(x_1^n, x_1^s) = p_1^n = MC_i^n(x_1^n)$$

Assuming that x_1^n is positive, the introduction of the natural product leads to substitution between the two products, reducing the demand for the synthetic product. Specifically, $P_1^s(x_1^s, 0) > P_1^s(x_1^s, x_1^n)$ reflects the decline in the price and quantity of the synthetic product$x_1^s < x_0^s$ & $p_1^s < p_0^s$. As consumers in the niche market exhibit a higher willingness to pay for natural products, the price of the natural product is likely to exceed that of the synthetic product $p_1^n > p_1^s$.

This process is illustrated in Figure 2. The right-hand panel of Figure 2 depicts the outcomes in the synthetic market. The introduction of the natural product shifts the demand for synthetic products downward, reducing both price and quantity, which may prompt synthetic producers to respond strategically. The left-hand panel of Figure 2 highlights the characteristics of the natural product market, where a higher willingness to pay and relatively inelastic demand result in a higher price and smaller equilibrium quantity compared to the synthetic product.

Description to Figure 2: The left panel represents the natural product market, while the right panel illustrates the synthetic product market.

Scenario $i = 0$: The baseline assumes a competitive synthetic market. Demand is given by P_0^s and supply is represented by MC_i^s. Equilibrium is determined at the intersection of demand and supply.

Scenario $i = 1$: The natural product is introduced, with demand P_1^n in the natural market. Substitution effects lead to a decline in demand for the synthetic product P_1^s shifting its demand curve downward and to the left. This results in a lower equilibrium price and quantity for the synthetic product.

Scenario $i = 3$: A monopoly exists in the synthetic market, while the natural market remains competitive. There is an interlinked relationship between the structure of the synthetic market and the demand for the natural product. The monopolist restricts synthetic output to maximize monopolistic profit, but the introduction of a competitive market for natural based product, reduces the effective demand that the monopoly in the synthetic market observes.

Note: Scenario $i = 2$, which assumes a monopoly in the synthetic market with no natural market, is not depicted in the figure.

Scenario $i = 2$: This scenario reflects a monopoly in the synthetic market and no natural products (4). Scenario $i = 2$ serves as an additional benchmark because it is reasonable to assume, as happened in the beta-carotene market, that synthetic producers initially possess monopoly power.

$$\max_{x_2^s} \{P_2^s(x_2^s, 0)x_2^s - C_2^s(x_2^s)\} \tag{4}$$

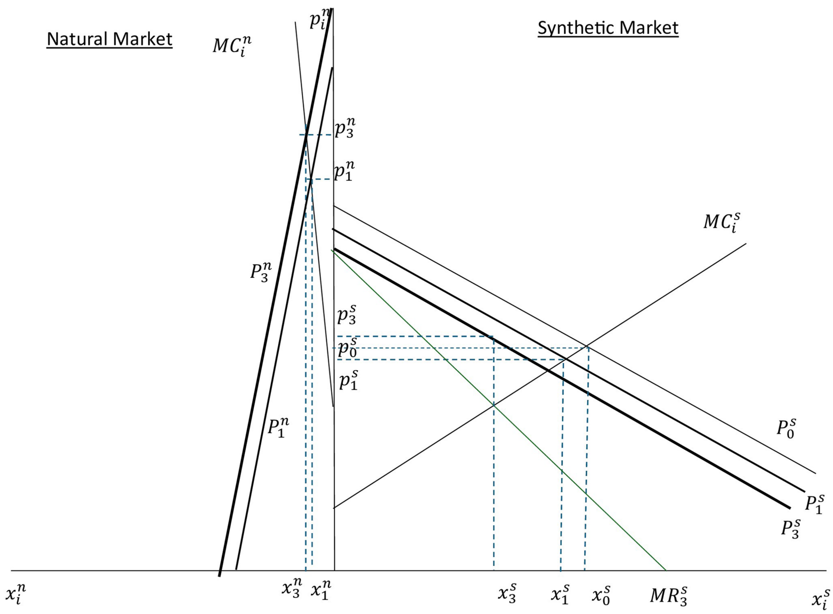

Fig. 2. Equilibrium in the synthetic market and competitive natural market (i = 0,1,3).

Unlike the competitive case in Scenario $i = 0$, the monopolist in the synthetic market observes the downward-sloping demand curve and maximizes profit by equating marginal revenue (*MR*) with marginal cost (*MC*), leading to a lower quantity and a higher equilibrium price compared to the competition *(Scenario* $i = 0$). Formally, the profit-maximizing condition is given by:

$$MR_2^s(x_2^s, 0) = P_2^s(x_2^s, x_2^n) + \frac{\partial P_2^s(x_2^s, x_2^n)}{\partial x_2^s} x_2^s = MC_2^s(x_2^s)$$

The reduction in output relative to the competitive benchmark reflects the monopolist's strategy of restricting supply to increase prices and extract additional profit from the market.

Scenario $i = 3$: Monopoly in the synthetic market and introduction of a competitive natural market. The profit-maximization problems for the two markets are:

$$\max_{x_3^s} \{P_3^s(x_3^s, x_3^n)x_3^s - C_3^s(x_3^s)\} \tag{5}$$

$$\max_{x_3^n} \{P_3^n(x_3^n, x_3^s)x_3^n - C_3^n(x_3^n)\} \tag{6}$$

Under this scenario, the monopolist in the synthetic market sees a downward-sloping demand. The monopolist will set the price where the marginal revenue equals the marginal cost in the synthetic market. In contrast, the equilibrium condition in the natural market equates inverse demand to supply. In particular, the equilibrium conditions are:

$$MR_3^s(x_3^s, x_3^n) = P_3^s + \frac{\partial P_3^s}{\partial x_3^s} x_3^s = MC_3^s(x_3^s)$$

$$P_3^n(x_3^n, x_3^s) = p_3^n = MC_3^n(x_3^n)$$

There is an interlink between the market structure of the synthetic product and the demand for the natural product. Due to the substitution with natural product, the monopoly in the synthetic market reduces the quantity traded, $x_3^s < x_2^s$, and reduces the price, $P_3^s < P_2^s$. Moreover, the synthetic monopolist will produce less and charge more than if the synthetic product were produced competitively (Scenario $i = 1$). The higher price in the synthetic market under monopoly, compared to competition, increases demand for the natural product, driving up its price. This feedback loop between the synthetic and natural markets continues until a new equilibrium is simultaneously reached in both markets. At this equilibrium, both the price and quantity in the natural market are higher than under competition, while the price in the synthetic market is also higher, but its quantity is smaller. These dynamics are illustrated in Figure 1, which compares Scenarios 0, 1, and 3.

$$x_3^s < x_1^s < x_0^s,$$

$$p_3^s > p_1^s > p_0^s,$$

$$x_3^n > x_1^n,$$

$$p_3^n > p_1^n.$$

Our analysis suggests that the synthetic producer, the incumbent in the industry, is losing from the entry of the natural product, which reduces the quantity sold and its price. The incumbent may worry about further losses from the expansion of the natural product and may attempt to merge and acquire the natural-product producers, thus controlling both markets.

Scenario $i = 4$: Two independent monopolies control each market. In this case, the marginal revenue in each industry is equal to the marginal cost:

$$MR_4^s(x_4^s, x_4^n) = P_4^s + \frac{\partial P_4^s}{\partial x_4^s} x_4^s = MC_4^s(x_4^s)$$

$$MR_4^n(x_4^n, x_4^s) = P_4^n + \frac{\partial P_4^n}{\partial x_4^n} x_4^n = MC_4^n(x_4^n)$$

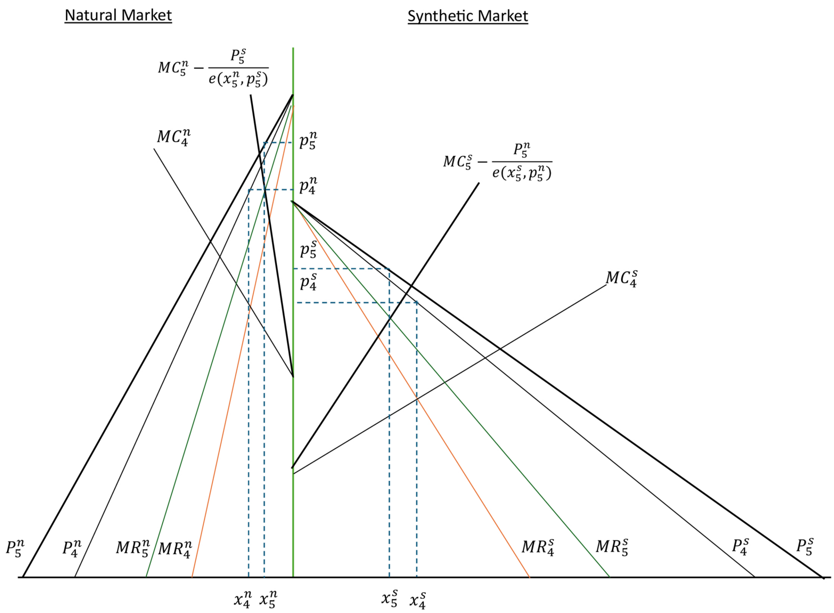

Fig. 3. Monopoly in each market vs. integrated monopoly (i = 4,5).

Figure 3 depicts the outcomes of scenarios 4 and 5. Obviously, with monopolies in both markets, prices increase, and quantities decline compared to the competition in Scenario $i = 3$. However, one possible outcome is that the synthetic monopoly takes over the production of the natural substitute, as we explain in the next scenario.

Description to Figure 3: The figure compares the outcomes under two scenarios:

Scenario $i = 4i$: Independent monopolies in the synthetic and natural markets. Each monopoly maximizes its profit independently, with no consideration of the interdependence between the two markets. Equilibrium prices and quantities in each market are determined solely by their respective demand and marginal cost curves.

Scenario $i = 5i$: An integrated monopoly maximizes profit across both markets, taking into account the impact of equilibrium conditions in one market on the other. This is reflected in the cost adjustment term $\frac{P_5^n}{e(x_5^s, p_5^n)}$ for the synthetic market, and symmetrically $\frac{P_5^s}{e(x_5^n, p_5^s)}$ for the natural market. The integrated firm sets higher prices and lower quantities in both markets compared to independent monopolies, with reduced output in one market increasing demand and prices in the other. This interdependence is symmetrical between the two markets.

Scenario $i = 5$: This scenario considers a horizontal monopoly where a single integrated firm controls both synthetic and natural markets, representing a case where the incumbent synthetic producer acquires the natural product startup. The firm solves a joint optimization problem to determine the optimal prices and quantities in both markets:

$$\max_{\{x_5^s; x_5^n\}} [P_5^s(x_5^s, x_5^n)x_5^s - C_5^s(x_5^s) + P_5^n(x_5^n, x_5^s)x_5^n - C_5^n(x_5^n)] \tag{7}$$

Obtaining the first-order conditions *(F.O.C.)* to determine the optimal production of synthetic and natural products from the derivative of the objective function in (7) clarifies that to maximize profit in the integrated markets, the monopoly should consider the marginal revenue, the marginal cost, and the substitution impact on the other market. Thus, the derivative of the first expression to x_5^s is $MR_5^s(x_5^s, x_5^n)$, the second is $MC_5^s(x_5^s)$, the third is the cross-price elasticity. Let $e(x_i^s, p_i^n) = \frac{\partial x_i^s}{\partial P_i^n}\frac{P_i^n}{x_i^s}$ to denote the cross-price elasticity of the synthetic product to the price of the natural product. The cross-price elasticity is positive because of the substitution between the natural and the synthetic products. Similarly, $e(x_i^n, p_i^s) = \frac{\partial x_i^n}{\partial P_i^s}\frac{P_i^s}{x_i^n}$ is the cross-price elasticity of the natural product with respect to the price of the synthetic product. Leading to F.O.C. in the synthetic market:

$$P_5^s + \frac{\partial P_5^s}{\partial x_5^s}x_5^s - MC_5^s(x_5^s) + \frac{\partial P_5^n}{\partial x_5^s}x_5^n = 0 \tag{8a}$$

Accordingly, the following holds:

$$MR_5^s(x_5^s, x_5^n) = MC_5^s(x_5^s) - \frac{P_5^n}{e(x_5^s, p_5^n)}$$

Similarly, for the natural market

$$MR_5^n(x_5^n, x_5^s) \equiv P_5^n + \frac{\partial P_5^n}{\partial x_5^n}x_5^n + \frac{\partial P_5^s}{\partial x_5^n}x_5^s = MC_5^n(x_5^n) - \frac{P_5^s}{e(x_5^n, p_5^s)} \tag{8b}$$

Finding the optimal x_5^s and x_5^n requires solving *F.O.C.* in equations (8a) and (8b) and provides significant insights. From (8a), at the optimal solution, the marginal revenue of the synthetic product equals its marginal production cost plus the marginal cost associated with the reduction of the price of the natural product as x_5^s increases. Similarly, from equation (8b), at the optimal solution, the marginal revenue of the natural product equals its marginal cost plus the marginal reduction in the price of the synthetic product due to increased production of the natural product.

Equations (8a) and (8b) suggest that when an integrated monopoly controls both natural and synthetic markets, the production of both products is lower than it would be under two independent monopolies. For independent monopolies, marginal revenue is equal to the marginal cost for each product. However, in an integrated monopoly, profit optimization decision has to account for the substitution effects between the two products. Accordingly, the marginal revenues are equal to the marginal cost of production plus the marginal cost of the reduced price of the substitute product. As Figure 2 illustrates, when a single company controls both markets, the prices of both products increase and quantities decline compared to the case of independent monopolies.

Scenarios 3, 4, and 5 represent highly realistic market conditions. The other scenarios have been included for comprehensiveness, providing a broad analytical perspective suitable for generalized economic analysis. Although this analysis covers only a subset of possible cases, additional scenarios merit consideration when the synthetic producer merges with the natural producer. One possibility is that the integrated monopoly utilizes its more extensive marketing network to expand demand for the natural product. Additionally, the synthetic firm may exploit technological advantages to reduce the production cost of the natural product, potentially increasing the natural-based output without reducing its price, while reducing the price and quantity of the synthetic product to maximize overall profit.

Alternatively, the synthetic producer may find that the costs of enhancing the natural product are too high and decide to sell the natural-based production, refocusing on expanding the synthetic market. Another possibility is that by owning the intellectual property for producing the natural product, the integrated firm may relocate natural production to a lower-cost location, thereby using or selling resources from natural production to optimize the firm's operations.

Moreover, the scenarios presented above are not mutually exclusive and may occur sequentially over time. Bio-based products may initially enter the market as a niche alternative to established synthetic products, benefiting from monopolistic markups. Over time, technological spillovers can facilitate entry by additional firms into the bio-based market, thereby increasing supply and reducing profit margins in both natural and synthetic markets. In parallel, the synthetic market structure may evolve from monopolistic competition toward vertical or horizontal integration, potentially including integration with suppliers of bio-based products.

Our case study reveals that many of these scenarios were relevant to the historical development of the beta-carotene industry. The integration between incumbent synthetic producers and developers of natural beta-carotene allowed major producers of beta-carotene to control competition between natural and synthetic alternatives, influencing prices, quantities, and overall market dynamics.

3. Development of supply chains from microalgae to β-carotene production

This section applies the conceptual framework from Section 2 to a new bioeconomy sector: microalgae-based β-carotene. It highlights key market elements and the complexities of its supply chain. This case study captures

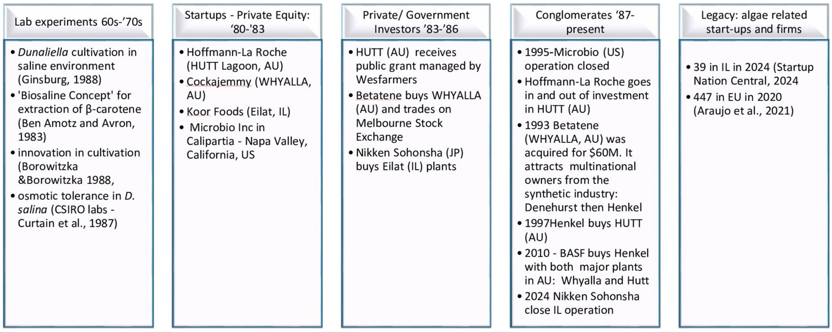

Fig. 4. Educational industrial complex: milestones of development of ISC and PSC in algae-based β-carotene.

multiple layers and nonlinearities, including the cultivation of natural inputs (*Dunaliella*), intermediate production (dry powder or oil concentration), processing, and marketing, with policy and learning influencing each stage. The supply chain involves aquafarmers as feedstock producers and integrators who purchase dry algae to extract β-carotene, which is then used by other producers for final products. In Australia, two main producers of *Dunaliella salina* were contracted by Hoffman-La Roche, a major synthetic β-carotene conglomerate. In Israel, a Japanese-owned vertically integrated operation cultivated algae in ponds, processed it into powder and distributed it through door-to-door agents. An early production effort in California, supported by Australian competitors, eventually closed due to unprofitable production systems. Nevertheless, natural product producers have maintained a legacy in the algae-based sector over the long term (Figure 4).

3.1. Innovation supply chain of *Dunaliella*

3.1.1. Lab investigation

The high growth rate of microalgae compared to that of terrestrial crops, combined with the ability of microalgae to accumulate a high content of lipids and sugars, positions them as a promising source for biofuels and other renewable products (Hochman and Palatnik, 2022). The identification of microalgae species capable of producing high lipid concentrations, like cellular oil, began in the 1940s (USDOE, 2010; Burlew, 1953), catalyzing research into their potential as feedstock for energy fuels during the 1950s and 60s (Ginzburg B.-Z., 1993; Meier, 1955; Oswald and Golueke, 1960). This focus expanded in the 1970s, particularly in the face of the fossil fuel crisis, prompting extensive biotechnological research aimed at conserving natural resources (Hochman and Palatnik, 2022).

In Australia, this research took a significant step forward in 1978 with the commencement of laboratory-scale research at the Roche Research Institute of Marine Pharmacology in Dee Why, Australia (Moulton, 1987). Roche was the world's producer of synthetic β-carotene with over 90 per cent market share and viewed algal production both as a potential way to reduce production costs and capture a market for a natural product.

Since 1980, comprehensive quantitative studies on the biology of the Dead Sea in Israel were underway (Ben-Amotz and Avron, 1980), and it was serendipitously discovered that the unicellular alga *Dunaliella* thrives in environments with extreme salt concentrations (Ginzburg, 1988). Margaret Ginsburg's discovery was a turning point, propelling the field from basic laboratory research to large-scale cultivation and the exploration of high-value industrial applications (Figure 4).

3.1.2. Applications

As the production of biofuels from microalgae proved to be expensive, while oil prices dropped in the mid-1970s, researchers began to explore other algae-based applications. Early research on *D. salina* focused on glycerol applications (Borowitzka and Brown, 1974). However, the low price of glycerol prompted the investigation to explore other, higher-value applications. *Dunalliela's* potential as a natural source of β-carotene led to trial operations in the USSR (Masyuk and Abdula, 1969), Israel (Ben-Amotz and Avron, 1980), California, the USA, and Australia (Borowitzka, Borowitzka and Moulton, 1984).

The 'Biosaline Concept', pioneered in Israel by Ben Amotz and Avron (1983), sought to exploit organisms adapted to arid, saline environments. The rise of molecular genetics further enhanced the ability to modify these organisms to increase their productivity and diversity of products. Follow-up research showed that this microalga thrives even in saturated brine solutions and can produce β-carotene up to 10 per cent of the dry weight (Ben Amotz, 1995), a concentration five to ten times higher than most algae.

The β-carotene derived from this alga is unique due to its stereoisomeric[1] composition, differing from the synthetic β-carotene available on the market. This difference gives algal β-carotene a higher quality suitable for various applications, particularly in natural food coloring, nutraceuticals (Burri, 1997; Epstein, 1973; Marino et al., 2020), and cosmetic industries (Ben-Amotz A., 1999). The innovators expected that these advantages could raise consumer preference for 'natural' over 'synthetic' food additives; the main market for β-carotene being as a colorant and pro-vitamin A (Ward, 2014).

3.1.3. Upscaling

Dunaliella has been cultivated intensively since the 1980s as a commercial source of natural β-carotene in (> 10 tonnes (t) dry biomass per annum) Australia (Borowitzka and Borowitzka, 1988), Israel (Ben-Amotz and Avron,

1 Molecules with the same formula and bonded atom sequence but different three-dimensional orientations. This spatial difference can improve the effectiveness or safety of drugs or nutrients.

1990), and Sapphire Energy Inc. in the USA (White and Ryan, 2015), followed by China (Gao, 1998). Focusing on salt-resilient microalgae to generate high-value-added products in freshwater-stressed regions where almost all commercial-scale algal biomass production was carried outdoors in natural light (Borowitzka and Vonshak, 2017).

The cultivation technologies are geographically dependent. Due to land scarcity, cultivation in Israel developed primarily in inland paddlewheel-driven raceway ponds near Eilat (Ben-Amotz and Avron, 1990) or in sleeves. In contrast, Australia's two research teams have grown the algae in very large and shallow natural saline onshore ponds (∼20-cm deep). The first group, Roche Algal Biotechnology, developed its pilot plant at **Hutt Lagoon**, Western Australia (Borowitzka, Borowitzka and Moulton, 1984), an outcome described in scenario 1 of the analytical model. The Australian government then took up this operation in 1984 contracting Wesfarmers Algal Biotechnology to carry out a second stage of piloting (Borowitzka, Moulton and Borowitzka, 1985). Next, the project was taken over in 1986 by Western Biotechnology Ltd, which built a 25 ha production plant based on favorable results from the pilot plant.

The second Australian group, at **Whyalla** in South Australia, focused on a low-cost recovery in open, unstirred, shallow ponds (Ward, 2014), which was the key to the economics of producing the pigment from algae. This technique came from earlier research that had been done into the mechanisms of halotolerance in *D. salina* in the hope that one day, these mechanisms might be transferable to other organisms using the new tools of genetic engineering (Curtain, West and Schlipalius, 1987). A pilot plant, capable of treating up to 400 liters of brine culture per day, was built in 1982 by CSIRO and start-up Cockajemmy Pty Ltd. The development was financed by ∼$250,000 of private equity matched by a government grant.

3.2. Production supply chain of *Dunaliella and* β*-carotene*

The commercialization of β-carotene production emerged from the educational, industrial complex that allowed collaborations between academic researchers and industry innovators. In Israel, a partnership between researchers from the Weizmann Institute (Ben Amotz and Avron) and Koor Foods, an Israeli conglomerate specializing in agriculture, led to the first commercial production. In Australia, Borowitzka and Borowitzka, as members of Roche Algal Biotechnology, established a production facility at Hutt Lagoon. Similarly, Curtin and the team of researchers in CSIRO Institute, partnered with Betatene to set up production in Whyalla, South Australia. These academic–industry–government collaborations were instrumental in transitioning β-carotene production from research to commercial success. With a long history of algae consumption and less stringent regulations than those in the USA and the EU, the Japanese market has become the primary algal β-carotene market. The Japanese distributors required producers to increase the concentration of β-carotene (in oil), prompting further innovation. The additional requirement to enter the Japanese market was the presence of at least two producers to ensure the security of supply. Thus, Australian (HUTT) producers elected to share part of their technology with a California producer. Heterogeneity of conditions and diversity of opportunities led each producer to develop a slightly different product:

- Hutt Lagoon (AU) and California (US) plants: These producers focused on extracting β-carotene in oil, targeting the high-value β-carotene market. Their product was similar to the synthetic version produced by companies like Roche, but at a higher environmental quality.
- Whyalla (AU): Aimed to produce natural β-carotene for the health food market and algal meal for animal feed.
- Eilat (IL): Dried algae containing β-carotene were initially limited in the dietary supplement market due to high salt content from growth in saline conditions. Subsequent research resolved this issue by developing a process to wash out the salt during production, making the product more marketable.

In Israel, the startup Nature Beta Technologies (NBT), which produces *Dunaliella* feedstock and powder β-carotene, was acquired by Nikken Sohonsha Corporation in Japan in 1989. Nikken Sohonsha sold the product door-to-door and has been profitable for 30 years. However, it was a small-scale operation, and a change in management leadership led to the closure of the plant in Israel in 2024. For three decades, the operation was economically viable. However, subsequent cost-cutting measures introduced by new management, particularly the elimination of biological expertise, eventually disrupted production processes (personal communication with Professor Shaish). The company had initiatives to develop a more advanced facility in China. Israel has found alternative applications for microalgae that leverage the knowledge gained from β-carotene, as shown below.

This example highlights the fundamental difference between synthetic and bio-based technologies that involve living organisms under changing conditions. It is crucial to maintain ongoing research and development with a focus on both biological and technological expertise. Sustaining interdisciplinary R&D capabilities not only ensures the effective management of technologies that rely on living organisms but also promotes innovation and the exploration of new market opportunities. This dynamic relationship exemplifies a feedback loop between the ISC and the PSC that is crucial for the bioeconomy.

The US experience in Sapphire Energy Inc., was marked by economic challenges. The American company's use of raceways, a technology they used to treat wastewater, was hindered by the need to transfer water for long distances and add salt, which added a significant cost. This financial burden ultimately led to the project's closure in 1995, highlighting the economic challenges in commercializing and upscaling natural-based β-carotene production, which lost the competition to the Australian producers.

The two Australian start-ups at Hutt Lagoon and Whyalla followed different funding paths, each developing distinct cultivation technologies and attracting investors based on their comparative advantages (Figure 4). Initially, Hoffman-La Roche, a leading producer of synthetic β-carotene, invested in both companies, likely driven by potential cost benefits from biosynthetic production and growing demand for natural products. However, Roche's involvement was inconsistent and included periodic re-evaluations of its investment. While Whyalla facility remained privately owned, Hutt Lagoon received significant government funding following Roche's initial investment. Once this funding ended, Hutt Lagoon sought new investors. At this stage, the intellectual property was acquired by Western Biotechnology Ltd, a publicly listed competitor in Australia. A few years later, Roche purchased all the shares of Western Biotechnology and resumed operations at Hutt Lagoon, but later sold the facility to Coogee Chemicals, a Western Australian company. Subsequently, Henkel, a German multinational that had acquired the Whyalla operations for $60 million, purchased Western Biotechnology and consolidated operations at both Hutt Lagoon and Whyalla. Managing both sites enabled economies of scale, knowledge transfer, and risk sharing, as adverse weather conditions were less likely to affect both locations simultaneously (Curtain., 2000). Henkel was managed by Lehman Brothers, and against the background of the financial crisis of 2008, BASF—the European multinational chemical company—acquired the operation in 2010. By 2021, BASF was one of the two dominant firms of biomass-based β-carotene production (Hochman and Palatnik, 2022).

Initially, the synthetic beta-carotene market was relatively competitive, dominated by major firms (e.g. Roche). They sought comparative advantage through investments in natural-based technologies. However, as this venture did not materialize quickly enough to satisfy private firm yields, funding increasingly came from government bodies and venture capital. When algae-based beta-carotene technology was successfully developed and introduced, market conditions evolved toward a scenario resembling monopolistic competition in both natural and synthetic beta-carotene markets (Scenario 4). Despite being a niche player, the algae-based beta-carotene significantly impacted the revenues of major synthetic producers. Eventually, synthetic conglomerates responded by integrating both synthetic and natural beta-carotene production, streamlining their supply chains and enhancing overall profitability (Scenario 5).

4. β-Carotene market at present and the legacy of the industry

The beta-carotene has grown to 39 per cent market share in 2023 (GVR, 2023a) with annual sales estimated between USD 500 million and billion (GMI, 2023; GVR, 2023a). The USA leads in North American consumption, driven by growth in the expanded use of β-carotene in food and beverage. Algae-based pigments, primarily from *D. salina*, lead the sector, particularly in Australia, with its large-scale operations (MeticulousResearch, 2023). Challenges remain in colder regions, where indoor cultivation is necessary, increasing costs. Conversely, regions such as South Africa, Namibia, Saudi Arabia, the United Arab Emirates, India, and China offer favorable climates for algae production, although site-specific issues need to be addressed. The production of β-carotene from *Dunaliella* required organic solvents in extraction or supercritical extraction with carbon dioxide. Early developments in this field have laid the groundwork for broader applications in algal biotechnology (Ward, 2014). *Dunaliella*-based β-carotene faces competition with cheap synthetic alternatives. Microalgae remain in niche markets in aquaculture, where they are used as feed for fish and prawns.

The initial focus on algal biofuels was deemed economically unviable (Stephens et al., 2010), but this pivoted attention toward higher-value products like carotenoids and Omega-3 fatty acids. A key legacy of the *Dunaliella* β-carotene industry is the development of cultivation and processing technologies, which now benefit other sectors such as *Spirulina* (which became a 'super-food'), extraction of astaxanthin, and even algae-based carbon capture technologies.

Astaxanthin, a keto-carotenoid primarily sourced from the microalgae *Haematococcus pluvialis*, has become a prominent product due to its antioxidant properties and health benefits (Ambati et al., 2014). In 2023, natural-based astaxanthin had more than 50 per cent of the $2.3 billion astaxanthin market; industry sources project this market to grow by 16 per cent annually between 2024 and 2030 (GVR, 2023a).

Emerging markets for algae-based products, such as fish oil replacements and fish meal, are expected to drive further development (GMI, 2023). While regulatory hurdles remain (Federal Ministry of Food and Agriculture, 2023), especially for products like astaxanthin, algae's unique properties make it well-positioned to thrive. About 39 algae-based start-ups operate in Israel (Startup Nation Central, 2024) and about 442 in the EU (Araújo et al., 2021).

5. Discussion

The case study of natural β-carotene illustrates the emergence of sectors of the science-based new bioeconomy. The evolution of the β-carotene industry highlighted the synergetic relationship between innovation and production supply chains. The discovery of high β-carotene concentration in *Dunaliella* in a saline environment (Ginsburg, 1988) and the invention of the 'Biosaline Concept' for extracting β-carotene from the *Dunaliella* (Ben et al., 1983) laid the foundation for the development and commercialization of β-carotene products. Insights of Academic Researchers and their involvement have been essential for establishing the β-carotene sector, consistent with the notion of the educational industrial complex, where publicly-supported university research provides some basic ideas that trigger economic growth and industrial development (Zilberman et al., 2018).

The analysis of the evolution of the β-carotene supply chain not only sheds light on the tradeoffs between synthetic and natural products but also instills a sense of optimism about the potential of the natural β-carotene industry. As emphasized by the conceptual framework of this study, learning by doing is essential for the industry to grow and thrive. In the case of β-carotene, the incumbent synthetic firms acquired control of the natural-based technologies and increased their market share and usage.

The introduction of the natural β-carotene industry has not only led to the invention and introduction of new and superior technologies but also inspired the development of other bio-based products (Golberg, 2020; Prabhu et al., 2020). This knowledge and experience accumulated in creating the β-carotene sector left a rich legacy that contributed to the emergence of other algae-based products (Fernandez et al., 2021; Golberg et al., 2020; Polle et al., 2020). The evolution of micro-algae industries benefiting from the knowledge externalities of the β-carotene sector illustrates a process where new products rely on the foundation of previous ones (Chalermthai et al., 2022). Microalgae investigation contributes to science in multiple directions (Yehuda et al., 2022). Natural β-carotene has contributed to technologies that have helped other products (Rahman, 2020).

New utilization of microalgae relies on recombinant innovation, where existing technologies are adapted and applied to new contexts. This cross-pollination of ideas and techniques accelerates the innovation process and enhances the ability of bio-based industries to overcome technical and economic challenges. The technological change in one sector of an economy stimulates endogenous growth via spillover effects into other parts (Acemoglu and Azar, 2020). The size and direction of the growth effect will depend on the organization of the supply chains within the economy.

While the natural β-carotene market did not achieve exceptional success and was eventually consolidated by companies producing synthetic alternatives, the process nonetheless catalyzed valuable technological advancements that have significantly contributed to the broader bioeconomy. Such outcomes, we argue, are more representative of innovation processes than dramatic successes. We believe our paper provides a novel perspective and contributes meaningfully to the understanding of real-world economic dynamics in emerging bioeconomy markets.

6. Conclusions

The bioeconomy utilizes new life sciences knowledge to produce a wide range of products from living organisms and the waste they generate. It is a significant component of sustainable development (Zilberman et al., 2018). This paper explores the evolution of β-carotene production through innovation and supply chains, as conceptualized by Zilberman et al. (2022). Innovating new products and building supply chains to produce and distribute them are essential to meet the needs of the growing global population sustainably. However, innovators seeking investment are adversely affected by various sources of uncertainty (Drabik and Wesseler, 2024). This paper examines the evolution of innovation and product supply chains in the β-carotene industry, utilizing a case study of microalgae-based production to elucidate broader principles pertinent to the bioeconomy.

First, public support for research and education is crucial for providing the foundation for human capital and discoveries that may spawn new industries. Technology transfer from universities to the private sector and engagement of academic researchers with industry are also essential foundations for developing new sectors.

Second, bioeconomy sectors may initially encounter cost disadvantages compared to established industries, yet they offer significant social benefits. To fully realize their potential, these sectors must stimulate demand for the unique characteristics of bio-based products. Given the positive externalities produced by the bioeconomy, policymakers should consider providing compensation for the societal benefits these industries create. Within reasonable limits, early public support is crucial to facilitate learning-by-doing and to develop the critical mass of knowledge and human capital necessary for long-term success. There are two key regulatory challenges: first, the need for research support covering both stages of the innovation supply chain—basic knowledge generation, as well as product development and upscaling—with potential encouragement of public-private partnerships. Second, regulation should be science-based to minimize delays and uncertainties in the regulatory process (de Figueiredo Silva et al., 2023). When bioeconomy activities contribute more to social benefits than private ones (e.g. pollution reduction), regulators should ensure appropriate compensation.

Third, predicting which specific products will succeed is challenging. The supply chain must experiment with different products and formulations, remaining flexible to adapt to variation in regulation, market demands, and consumer preferences.

Fourth, building creative innovation supply chains provides multiple dividends—they create the knowledge that leads to knowledge and skills spillover, where one discovery begets another.

The bioeconomy is in its infancy, and while harnessing bioresources presents initial challenges, the case of beta-carotene demonstrates that it is a journey filled with both setbacks and rewarding breakthroughs.

The bioeconomy presents significant frontiers for economic research. The analysis of innovation and production supply chains is crucial for a deeper understanding of the emergence of markets and institutions. In certain contexts, contractual relationships may be more critical than market prices. Furthermore, advancing scientific research through close collaboration with industry stakeholders and developing robust empirical case studies are essential. Enhancing our analytical capabilities to investigate the dynamic evolution of market structures is central to comprehending these emerging sectors. Effective policy development must carefully consider economic, political, and biophysical constraints inherent in the expansion of the bioeconomy.

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