

Survey

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Biological engineering as a driver of innovation: implications for the economy

Biologiebasierte Ingenieurwissenschaft als Innovationstreiber: Wirtschaftliche Implikationen

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Abstract: The world economy's growth has devastated the environment, risking resource scarcity. Recognizing the urgency, various business concepts aim for triple bottom line goals – ecological, economic, and social. Biological engineering emerges as a promising solution, utilizing renewable biological resources to address global challenges. This paper explores its role across sectors like novel materials and agriculture, shifting focus to economic implications, especially in startup ventures. By examining global startups' distribution and venture capital investments, it highlights their role in driving innovation and economic growth. It underscores biological engineering's potential in addressing environmental challenges and fostering prosperity through innovative startups, bridging science and business for sustainability.

Keywords: biological engineering; startups; bioeconomy; venture capital investment

Zusammenfassung: Das weltweite wirtschaftliche Wachstum hat die Umwelt massiv geschädigt und eine Verknappung der Ressourcen bewirkt. Diese Dringlichkeit erkennend, zielen viele Geschäftskonzepte darauf ab, die Ziele der Triple Bottom Line umzusetzen – ökologische, ökonomische und soziale Ziele. Biologisches Ingenieurwesen entstand als eine vielversprechende Lösungsmöglichkeit, indem erneuerbare biologische Ressourcen verwendet werden, um globale Herausforderungen anzugehen. Diese Studie untersucht die Rolle von biologischem Ingenieurwesen im Hinblick auf unterschiedliche Sektoren wie neue Materialien oder Agrarwirtschaft und richtet den Blickwinkel auf

die wirtschaftlichen Auswirkungen, insbesondere hinsichtlich Start-ups. Indem die globale Verteilung dieser Start-ups und ihre Venture-Capital-Investitionen untersucht werden, wird deren Rolle als Treiber von Innovation und wirtschaftlichem Wachstum hervorgehoben. Dies unterstreicht das Potenzial von biologischem Ingenieurwesen, umwelttechnischen Herausforderungen zu begegnen und Wohlstand durch innovative Start-ups zu unterstützen, indem Wissenschaft und Wirtschaft im Hinblick auf Nachhaltigkeit verbunden werden.

Schlagwörter: Biotechnologie; Start-ups; Bioökonomie; Risikokapitalinvestitionen

List of abbreviations

APAC	Asia – Pacific
CO ₂	carbon dioxide
et al.	et alia
GBP	British pound
MIT	Massachusetts Institute of Technology
NAE	The U.S National Academy of Engineering
R&D	research and development
USD	United States dollar(s)
VC	venture capital

1 Introduction

The world economy has been driven by the principles of “take, make, waste” for the past two hundred-fifty years [1]. This linear pattern of production and consumption first created rapid prosperity thanks to the generosity of nature, where virgin material costs were getting lower and lower over time [2]. Nonetheless, minimal awareness about the non-renewability of natural resources and the devastation of the environment has been publicly raised for a long time. The depletion of renewable resources is expected to sharply rise [3], impacting agricultural land, forests, and biodiversity. As a consequence, future generations face widespread depletion of water resources, fisheries decline, and potential climate changes. The U.S. National Academy of Engineering

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(NAE) identifies 14 challenges in “sustainability, health, security, and joy living” [4]. Notably, engineering achievements have become commonplace in applying technology to fulfill human needs such as access to clear water, providing energy from fusion, and engineering the tools of scientific discovery etc. [4]. Furthermore, the lack of control over environmental issues has negatively affected the ecology and societies, thereby challenging human beings’ future [5]. These challenges have been the starting point for an increase in the awareness of sustainability. The ultimate goals thereby are set to simultaneously achieve the ‘triple bottom line’ by following ecologic, economic, and social goals [6]. As a response to this urgent need, a variety of business concepts have been introduced to either partially or entirely address the desired objectives, such as industrial ecology [7], cradle-to-cradle [8], closed-loop supply chains [9], the blue economy [10], resource efficiency [11], and reverse logistics [12]. The bioeconomy concept has been advocated as a set of promising solutions for “generation of renewable biological resources and the transformation of these resources and residual streams into products with added value, including food, feed, bio-based goods, and bioenergy” ([13]; pp. 01–02). Yoon & Riley [14] emphasize the crucial role of biological engineering in addressing global challenges in medicine, agriculture, and the environment. According to 14 challenges in the 21st century in “Grand Challenges for Engineering” of NAE, surprisingly, at least seven of these challenges can be tackled by using the tools and methods of biological engineering [14]. For instance, addressing “Develop carbon sequestration methods” involves optimizing bioreactor designs for algae biofuel yield, using synthetic biology to enhance carbon sequestration potential, and applying ecological engineering for efficient system interfaces [14]. This approach, though not eliminating carbon dioxide (CO₂) release, enables a genuine recycling process. Additionally, an academic department at Massachusetts Institute of Technology (MIT) states that the objective of a “biological engineering discipline is to advance fundamental understanding of how biological systems operate and to develop effective biology-based technologies for applications across a wide spectrum of societal needs including breakthroughs in diagnosis, treatment, and prevention of disease, in design of novel materials, devices, and processes, and in enhancing environmental health,” ([15]; pp. 01). The expansive field of biological engineering extends its focus to encompass the entire range of life sciences. This includes applications in agricultural, environmental, and ecological systems, employing engineering approaches and the rationale to address biological challenges, as articulated by

Johnson & Phillips [16]. This has resulted in advancements in biological engineering that hold the potential to bring benefits to a range of industries, including healthcare, food and agriculture, consumer products, sustainability, and energy and materials production, as highlighted by McKinsey Global Institute [17]. The potential societal and economic impact of biological engineering is considerable, as evidenced by theoretical projections indicating that biological processes may contribute up to 60 % of global physical inputs [18].

Given this importance of biological engineering for resource-saving products and services available in the future, the potential economic relevance of biological engineering is one interesting aspect to take a closer look at. Since the sector of biological engineering is based on very innovative technological advancements, it comes without surprise that many startups can be found in this industrial sector. This manuscript aims to provide a comprehensive overview of global active startups in the field of biological engineering, detailing their geographic distribution and current venture capital investments in key sectors, including agriculture, aquaculture, food, consumer products, human health, materials, chemicals, and energy. Additionally, it explores the growing capacity to understand and utilize biological processes, highlighting the potential economic benefits, such as the emergence of new business models and the creation of high-quality jobs, while emphasizing the role of biotech startups in bridging the gap between science and business.

2 The market relevance of the field biological engineering

The following chapter provides a comprehensive overview of the market landscape in the realm of biological engineering, encompassing an analysis of the current market status and an enumeration of the total number of operational startup companies in this sector.

2.1 Market overview

Despite the decisive role that biological engineering is expected to play in the future economy, as researchers, entrepreneurs, and various industry stakeholders unlock the potential of the next generation of biological technological innovations [19], it is still in the early stages of being recognized as an independent industry. In other words, some venture capital (VC) reports incorporate biological engineering into other industries. For example, agriculture includes Animal Husbandry, which involves businesses that

breed, raise, and market livestock. Chemicals and gases are classified as Industrial Chemicals, which includes producers of chemicals primarily used in industrial applications such as plastics, biocides, coolants, and polyglycols [20]. Similarly, Computational Biology and Chemical including Biofuels and Protein Design, Synthetic Biology and Lab-Grown Food etc., and Advanced Materials, Manufacturing & Recycling Technologies containing Bioplastic, Green Concrete and Graphene, etc., are also considered within the 2023 European Deep Tech Report [21]. In the year 2023, there was a noteworthy 50 % decline in the European venture capital investment within the biology and chemistry industry, decreasing from USD 505 million to USD 288 million [21]. Simultaneously, the VC investment in Novel Energy experienced a substantial decrease, plummeting from USD 1.3 billion to USD 656 million from 2022 to 2023 [21]. This downtrend is easily understood given the recent introduction of novel artificial intelligence (AI) technologies, such as ChatGPT by OpenAI. They contribute to accelerate investment cycles and returns by attracting more venture capital. This discernible trend is elucidated in the report of the VC investment in emerging Deep Tech startups in Europe (Figure 1) showcasing a decline in investment within industries such as novel energy and computational biology and chemistry where biological engineering significantly contributes to product development and innovation.

However, noteworthy examples of prosperous biological engineering startups, such as Ginkgo Bioworks (the US), Mushlabs (Germany), and CarbonWorks (France), offer concrete proof of the sector's promise. These role models support more research in the fields of biological engineering

and development initiatives. For example, Ginkgo Bioworks, founded in 2009 by MIT scientists, exemplifies a successful startup in the sector of biological engineering. Ginkgo Bioworks generates revenue through various streams such as product sales, technology licensing, research and development (R&D) services, partnerships, and investments by developing customized organisms to deliver sustainable and efficient solutions across various industries, including pharmaceuticals, food, agriculture, and industrial chemicals. Valued at over USD 15 billion today, Ginkgo has secured over USD 800 million in funding and collaborates with major corporations like Bayer and Roche. In the report as Biomanufacturing to Advance the Bioeconomy that has been recognized as a leading driver that resulted in an explosion of innovative new products that touch many aspects of people's life [19] with the estimation of the total impact in the economy of the US to be USD 959 billion [19]. In a more focused context, the United States has officially declared a financial commitment of USD 2 billion [19] for this industry. Simultaneously, the United Kingdom has communicated a noteworthy public investment of GBP 73.6 million in R&D within the field of biological engineering [22]. These commitments are in line with a burgeoning global trend, where nations including China, France, Germany, Japan, Singapore, Israel, and Denmark are strategically prioritizing engineering biology [22].

To delve further into the realm of VC within the field of biological engineering, it is crucial to intensively examine the numbers in both the US and European markets, which host the largest number of biological startup companies (Figure 3). Concerning the VC investments in the US market,

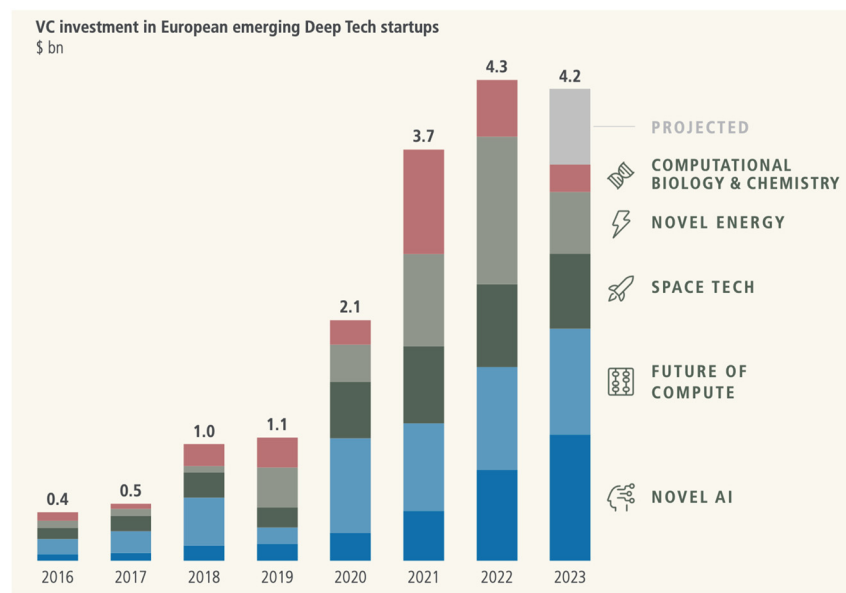


Figure 1: The venture capital investment in European emerging Deep Tech startups. Source: The 2023 European Deep Tech Report [21].

the most significant contributions in biological engineering products are observed in Life Science, Energy, and Commercial Products and Services. The figures for these sectors in 2023 were USD 43 billion, USD 5.9 billion, and USD 37.2 billion, respectively [20].

A more comprehensive perspective on the VC invested in Europe is available in the 2023 European Deep Tech Report [21]. Biological engineering is evident in various industries such as Computational Biology and Chemistry and Novel Energy. In the context of Novel Energy, the VC figures for Alternative Battery Chemistries & Supercapacitors, Nuclear Energy, and Hydrogen & Ammonia were USD 121 million, USD 121 million, and USD 86 million, respectively ([21]; p. 98). In terms of Computational Biology & Chemistry, where biological engineering products make a significant contribution, the venture capital investments reached USD 288.3 billion ([21]; p. 107).

Consequently, these enormous amounts invested in the biological engineering sector indicate the high awareness that is attributed to this sector. Moreover, the analysis delves into market dynamics and competition, promoting the contributions of both established entities and innovative startups within the biological engineering landscape.

2.2 Which sectors are likely to be most affected by bioengineering?

Chui et al. [18] and McKinsey Global Institute emphasize the transition of proof-of-concept experimentation from labs to markets, especially in health and agriculture, with biological alternatives gaining traction for enhanced efficiency and reduced environmental impact. While current biological engineering impacts are concentrated in health and agriculture, McKinsey Global Institute foresees substantial value emerging in four domains over the next one to two decades, notably in human health and performance. Beyond these domains, more than half of the anticipated impact is expected in agriculture and consumer products over the next ten to 20 years (Table 1).

Regarding the quantity of operational startups within the field of biological engineering, the data obtained from

Crunchbase (Figure 2) illustrates the worldwide distribution of companies across five different sectors with Healthcare/Pharma sector leading with 1933 startups, reflecting significant innovation. Meanwhile, second is the agriculture and farming sector, contributing 822 companies. Energy, material and waste management comprise 483 companies, while consumer products and services follow closely behind, contributing 459 companies to the global number. In contrast, food and beverage has the lowest number of active startups with 233 companies.

In order to delve deeper into the topic of operational startup companies in the field of biological engineering, Figure 3 represents the distribution of such operations across different world regions for the year 2023. Significantly, Africa offers a modest but evolving representation with 8 operational startups visible for biological engineering innovation on the continent. Joining forces in the Middle East and India amount to 101 operational startups. In the Asia and Asia-Pacific (APAC) region, 154 operational startups are present evidencing continued interest in biological engineering across various Asian countries. In Latin America, 170 operating startups are active, pointing towards a dynamic Central and South American market. In terms of biological engineering innovations, Europe becomes a dominant player with 500 operational startups showcasing its strong commitment, while North America is featured as an influential hub that have 761 establishments. More specifically, the U.S., in particular, has emerged as a global leader with over 600 operational startups that highlight its focus on innovation within the field of biological engineering (Figure 4). This regional distribution underscores the wide-spread importance of biological engineering in the entrepreneurial domain, revealing differences in accentuation and implementation across different continents (Figure 4).

Figure 5 illustrates the number of active startups among the 10 biggest countries after the United States. This ranking highlights the prominence of certain countries in fostering a thriving ecosystem of biological engineering startups, contributing to the sector's global advancement.

Hence, the market overview on existing startups in the domain of biological engineering provides valuable insights into the current landscape. The thorough information of

Table 1: Estimate of range of annual potential direct economic impact by domain, 2030–2040. Source: Own presentation based on Chui et al. [18].

Sector	Focusing areas	Estimated potential impact
Health and human performance	Reproductive medicine and drug development	USD 1.3 trillion
Agriculture, aquaculture, and food	Alternative proteins like meat lab-grown, plant-based protein	USD 800 billion to USD 1.2 trillion
Consumer products and services	Personalized consumer products and services based on individual biological compositions, beauty, and wellness	USD 200 billion to USD 800 billion
Materials and energy	New bioroutes for fabrics and dyes, and novel materials such as biopolymers	USD 200 billion to USD 300 billion

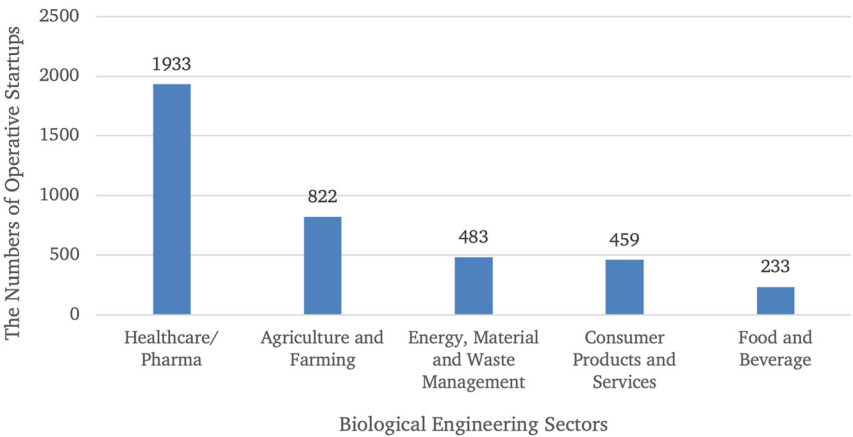


Figure 2: The global operational startup companies in biological engineering in 2023. Source: Own illustration based on the data of Crunchbase [23].

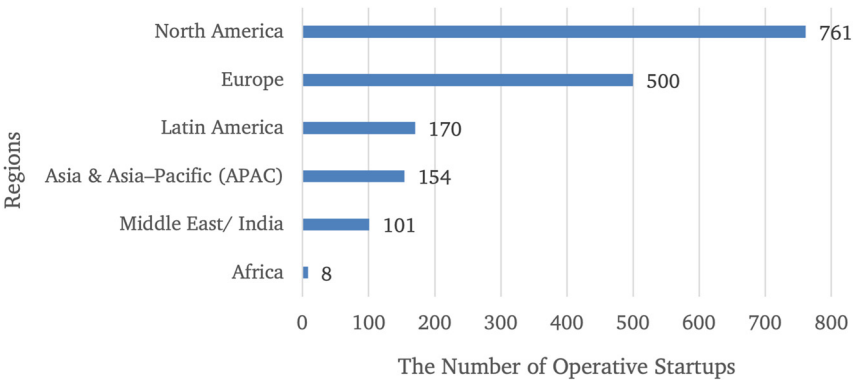


Figure 3: The global distribution of such startup companies across various regions in the year 2023. Source: Own illustration based on Crunchbase data [23].

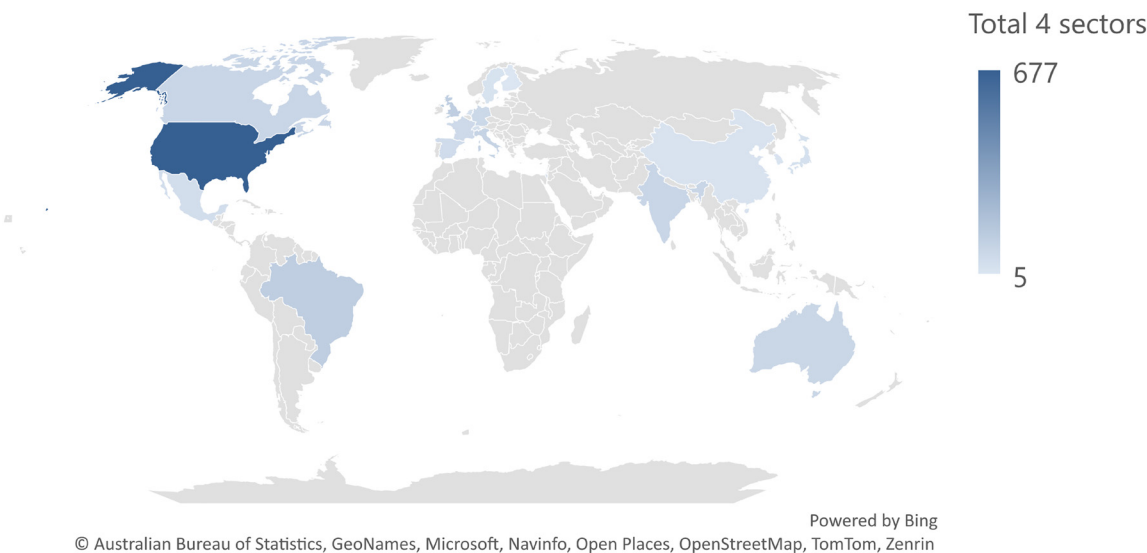


Figure 4: The global operational startup companies in biological engineering by regions in 2023. Source: Own illustration based on Crunchbase data [23].

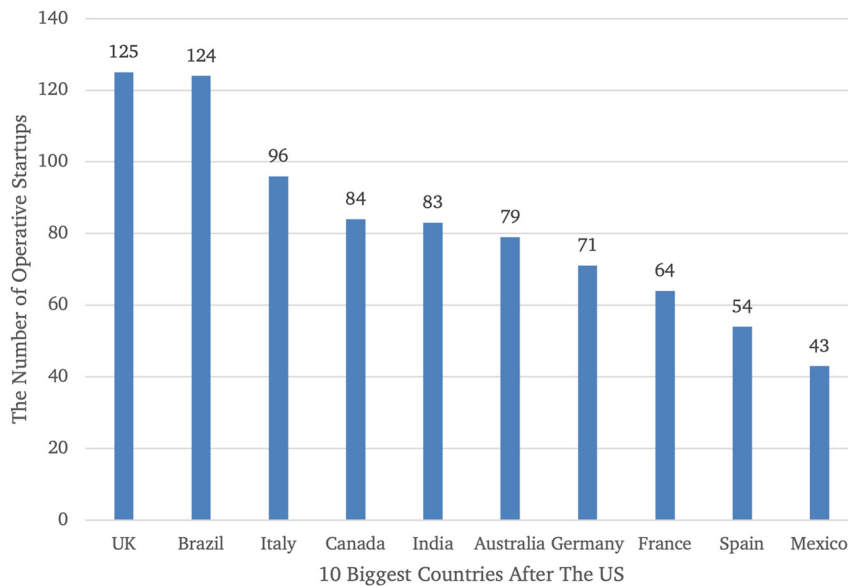


Figure 5: Active startups among 10 biggest countries after the United States. Source: Own illustration based on Crunchbase data [23].

operational companies and prevailing market conditions offers a foundation for understanding the dynamics shaping the industry.

3 Implication for the economy

This chapter provides a comprehensive overview of various economic implications, emphasizing the development of future businesses, as well as the convergence gap of business and science in the field of biological engineering. Additionally, it explores the creation of high-quality employment opportunities and a skilled workforce by economic activities in the domain of biological engineering.

3.1 The future of business

Entrepreneurial activities, often conducted collaboratively within organizational and academic settings [24], [25], are rooted in university labs serving as hubs for scientific research and career development. Biological engineering startups originating from universities capitalize on extensive research to pioneer transformative technologies. Initiated by students, faculty, or alumni, these startups leverage institutional resources to achieve leadership positions in their industries. Entrepreneurial labs within academic settings are now commonplace, bridging academia and entrepreneurship.

University efforts in entrepreneurial endeavors, facilitated by tech transfer offices, establish links between academia and venture capitalists. University-focused accelerators and incubators integrate entrepreneurial mindsets

into academic environments [26]. While academic pursuits receive systematic grant funding, entrepreneurial labs prioritize immediate impact, emphasizing product-market fit [27]. Harmonizing academic and entrepreneurial mindsets is vital for unlocking impactful innovation in the field of biological engineering.

Hence, establishing entrepreneurial labs and university startups necessitates fostering a culture dedicated to innovative problem-solving and embracing challenges and failures associated with entrepreneurship for success.

3.2 Bioengineering startups: bridging the gap between science and business

Biological engineering startups are pivotal in translating academic technologies into market-based applications [28]. Through biological technology, they craft pioneering products bridging scientific discoveries and commercial viability [28]. This discourse explores entrepreneurial initiatives in biological engineering, emphasizing the integration of science and business, the development of commercial offerings, the acquisition of intellectual property, financial backing, and collaboration with industry partners.

3.2.1 Integration of science and business

Establishing a science-driven business is crucial for emerging markets, where attention to scientific progress is limited, and the connections between academia and entrepreneurship are largely absent [29]. The biological engineering industry, akin to high-tech sectors such as software and

semiconductors, involves startups focusing on specific elements of the R&D value chain, engagement with the VC and public equity markets, and a market for expertise [30]. Thus, it significantly contributes to meeting the demands of both science and business, facilitating the revolution of R&D, addressing complex issues, developing innovative materials, and generating substantial economic wealth.

3.2.2 The unmatched speed and agility of small startups

While large corporations can meet innovative market demands due to their extensive resources, small startups possess a distinctive edge in terms of agility [31]. Like other entrepreneurs, biological engineering startups can swiftly adjust to market fluctuations, whether they involve changes in consumer demands, technological progress, or unexpected global events like a pandemic. This agility stems from their freedom from the bureaucratic complexities and time-consuming decision processes typically found in larger organizations.

3.2.3 Accessing to fundings and investment

Accessing venture capital and alternative fundraising avenues is critical for small biological engineering startups to compete with industry incumbents by innovating their products. Small biological engineering startups can obtain the necessary funding to expand their operations, compete with larger competitors, and exert significant market influence by effectively utilizing these financial resources.

3.2.4 Addressing niche markets

Large companies tend to disregard or perceive specialized or niche domains as excessively risky [32]. Through refining their proficiency in these specific markets, small biological engineering startups have the capacity to create unparalleled products and services tailored to particular, frequently underserved, customer segments.

3.3 Rising the high-quality jobs and workforce development

Bioscience startups, founded by scientists, play a crucial role in shaping employment, fostering an entrepreneurial spirit, and providing high-quality job opportunities [33]. The dynamic nature of bioscience work requires specialized expertise [34]. During the 1980s, biological science gained prominence in business and social research [35], founding its pivotal and definitive role in the context of

entrepreneurship startups. Rapidly expanding biological engineering startups offer diverse career prospects, necessitating multidisciplinary skills [33]. Despite potential uncertainties, the startup culture allows impactful contributions, from scientific discovery to intellectual property delivery, with opportunities for rapid career advancement, involvement in decision-making, and collaboration with industry leaders. While established firms traditionally offer higher wages, startup employees often receive share options, aligning their interests with company success. As startups grow, equity for employees increases, creating a unique incentive structure. Educational investments are crucial for the bioscience workforce, and government support is pivotal in driving basic science research licensed to private firms [36]. This unique incentive structure, educational investments, and government support underscore the significance of biological engineering startups in driving innovation and addressing real-world challenges in the evolving bioscience landscape.

4 Opportunities and threats

In the rapidly evolving field of biological engineering startups, there are abundant opportunities and significant challenges. These startups, driven by market demand, venture capital, and government interest, hold growth potential across various sectors (discussed in chapters 1 and 2). The potential for collaboration with large established companies and the global market presents a noteworthy opportunity. Startups in biological engineering have the opportunity to access niche markets (chapter 3.2), resulting in cross-border partnerships and collaborations such as Ginkgo Biowork realized. Committee on Science and Technology in Foreign Assistance et al. [37] emphasize that innovations in the sciences and associated technologies are not only originating within the domestic sphere, but also internationally. Embracing an early global perspective, as emphasized by Zieba [38]; enhances growth opportunities for these startups. The focus on innovation distinguishes biological engineering startups from the established players in the current market, positioning them as potential industry disruptors, and attracting investors. With the ability to address global climate change through sustainable practices, these startups contribute to environmental sustainability by developing non-nature resource-based materials.

However, amidst opportunities, biological engineering startups face substantial threats. Ethical considerations, mergers, and acquisitions (M&A), and the extended development cycle of the biological engineering innovation pose major challenges. A delicate approach is necessary due to

the ethical implications of manipulating biological systems and the potential societal repercussions. Additionally, there is a chance that this practice would assign people to a pre-determined life, which would further restrict their freedom of choice [39]. There are many different kinds of ethics, including theological, philosophical, cultural, and research-centered ethics [21]. It can be difficult to navigate in the fast-evolving regulatory environments of the sector since they change quickly to keep up with the fast-moving field of biological engineering.

Both opportunities and threats are introduced by venture creation and M&A. A startup's capabilities can be improved by resource consolidation through M&A, but there are integration challenges and possible disruptions. The journey from conceptualization to market release is not straightforward. Similarly, to other biological products such as drug or synthetic biology, biological engineering products also have a long-time development. In the initial stages, like target identification and lead optimization, numerous potential products are frequently eliminated. For small and young startups, this poses a challenge in advancing technology development due to limited resources and since developments in the field of biological engineering usually have a large financial need that needs to be financed mainly by venture capital investments which often are not available at the required size.

Hence, while biological engineering startups hold immense potential for innovation and global impact, careful consideration of ethical, regulatory, and resource-related challenges is essential for their sustained success.

5 Conclusions

In conclusion, the sector of biological engineering is promising in terms of its economic importance, which focuses on producing renewable biological resources and turning them into products with added value for a variety of industries. The interdisciplinary nature of biological engineering, encompassing fields such as biochemical, bioengineering, agriculture, and biomedical engineering, positions it as a key player in advancing technologies for societal needs [40].

The research areas within biological engineering, as explored in this paper, shed light on the critical role of biological engineering startups in the market. The analysis of active startups in various domains underscores the economic implications of biological engineering, including the creation of new industries and high-quality jobs. Moreover, the study emphasizes how biological engineering startups serve as crucial intermediaries bridging the

gap between scientific advancements and practical business applications. As the manuscript unfolds, it becomes evident that opportunities for economic growth and societal benefit are intrinsic to the endeavors of biological engineering startups.

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