Biotechnology Industry Analysis: Market Dynamics, Emerging Trends and Future Outlook

Nikhitha V. [1], Manwitha N. [2], Nayana G. [3] & P. S. Aithal [4]
[1] MBA Scholar, Poornaprajna Institute of Management, Udupi, 576 101, India,
Orchid ID: 0009-0003-1335-3606; Email: nikhitha.mbab24@pim.ac.in,
[2] MBA Scholar, Poornaprajna Institute of Management, Udupi, 576 101, India,
Orchid ID: 0009-0003-9976-3453; Email: manwitha.mbab24@pim.ac.in,
[3] MBA Scholar, Poornaprajna Institute of Management, Udupi, 576 101, India,
Orchid ID: 0009-0008-4286-0398; Email: nayanag.mbab24@pim.ac.in
[4] Professor, Poornaprajna Institute of Management, Udupi - 576101, India,
Orchid ID: 0000-0002-4691-8736; E-mail: psaithal@pim.ac.in

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Nikhitha V. [1], Manwitha N. [2], Nayana G. [3] & P. S. Aithal [4]

[1] MBA Scholar, Poornaprajna Institute of Management, Udupi, 576 101, India,
Orchid ID: 0009-0003-1335-3606; Email: nikhitha.mbab24@pim.ac.in,

[2] MBA Scholar, Poornaprajna Institute of Management, Udupi, 576 101, India,
Orchid ID: 0009-0003-9976-3453; Email: manwitha.mbab24@pim.ac.in,

[3] MBA Scholar, Poornaprajna Institute of Management, Udupi, 576 101, India,
Orchid ID: 0009-0008-4286-0398; Email: nayanag.mbab24@pim.ac.in

[4] Professor, Poornaprajna Institute of Management, Udupi - 576101, India,
Orchid ID: 0000-0002-4691-8736; E-mail: psaithal@pim.ac.in

ABSTRACT

Purpose: *This study aims to comprehensively analyze the biotechnology industry by examining its current trends, market dynamics, technological advancements, and future outlook. It focuses on understanding the impact of innovations such as artificial intelligence, genomics, personalized medicine, and biopharmaceuticals, while evaluating the role of government policies, investment patterns, stakeholder perspectives, and regulatory frameworks. The study also identifies the opportunities and challenges influencing the growth, sustainability, and global competitiveness of the biotechnology industry, with particular emphasis on the Indian biotechnology ecosystem.*

Methodology: *The study adopts exploratory research approach based entirely on secondary data. An extensive review of academic literature, industry reports, government publications, and published research articles was undertaken to examine the biotechnology sector. Multiple strategic analytical frameworks, including SWOC (Strengths, Weaknesses, Opportunities, Challenges), ABCD (Advantages, Benefits, Constraints, Disadvantages), and PESTLE (Political, Economic, Social, Technological, Environmental, Legal) analyses, were employed to evaluate both internal and external factors influencing the industry. Stakeholder perspectives including biotechnology companies, researchers, healthcare providers, policymakers, investors, and consumers were integrated to assess the implications of technological adoption, particularly Artificial Intelligence, across biotechnology operations.*

Results & Analysis: *The findings reveal that technological innovations such as Artificial Intelligence, machine learning, genomics, gene editing, bioinformatics, and personalized medicine are transforming the biotechnology industry by accelerating drug discovery, improving diagnostic accuracy, enhancing clinical trials, optimizing biomanufacturing processes, and enabling precision healthcare. The SWOC and ABCD analyses indicate that the industry possesses significant strengths in innovation, research capabilities, and market growth potential while facing challenges related to regulatory complexity, ethical concerns, cybersecurity, high research costs, data privacy, and shortages of skilled professionals. The PESTLE analysis further highlights that supportive government initiatives, increasing investments, sustainability concerns, and rapid technological developments are major drivers shaping the industry's future growth and competitiveness.*

Originality/Value: *This study provides a comprehensive and integrated assessment of the biotechnology industry by combining industry trend analysis with multiple strategic evaluation frameworks and stakeholder perspectives. Unlike conventional industry reviews, it establishes a multidimensional understanding by linking technological advancements, Artificial Intelligence adoption, regulatory developments, market dynamics, sustainability considerations, and innovation strategies within a single analytical framework. The research* *offers a holistic perspective on both current developments and the future direction of the biotechnology industry.*

Type of Paper: *Exploratory Research on Industry Analysis*.

Keywords: Biopharmaceuticals, Genomics and Personalized Medicine, Future Outlook, Innovation in Biotechnology, Emerging Technologies, Market Growth, SWOC Analysis, ABCD Analysis, PESTLE Analysis

1. INTRODUCTION :

The biotech sector is set for ongoing growth, fuelled by advances in genetic engineering, synthetic biology, and industrial technologies. This growth is fuelled by the ongoing advancements in gene-editing technologies, such as CRISPR, and the increasing demand for personalized medical treatments and sustainable bio-based products. Biotechnology's broad applications across industries indicate that it will continue to be a transformative force in the coming decades, shaping the global economy and improving quality of life (Musaeva (2023). [1]).

The biotechnology market today is marked by growth trends focused on precision and sustainability. In healthcare, biotechnology enables personalized medicine, tailoring treatments to an individual's genetic profile for better outcomes and fewer side effects (Pisano (2006). [2]). Simultaneously, industrial biotechnology is reshaping manufacturing by using biocatalysts and bio-based materials for sustainable production of chemicals, biofuels, and other products. As noted by Mussatto et al. (2010). [3] this shift supports global efforts to reduce carbon footprints and advance green technologies.

The future of biotechnology presents a wide range of possibilities, from the refinement of gene-editing tools to advances in regenerative medicine. As Sager (2001). [4] discusses, Biotechnology is anticipated to advance through the growing incorporation of artificial intelligence and machine learning, enabling more precise forecasting and accelerated treatment development. Scenarios for the future include the potential eradication of genetic disorders through gene therapies, breakthroughs in tissue regeneration, and even the growth of lab-grown organs for transplant (McKelvey et al. (2004). [5]). Furthermore, bio-ethanol production, which faces challenges such as efficiency and scalability, may become a critical component in achieving global sustainability goals (E Bhaskaran (2022). [6]).

In industrial biotechnology, innovation trends are pushing the boundaries of how products are made and consume. Emphasize the shift towards using microorganisms and enzymes as biocatalysts, which offer more sustainable and efficient alternatives to traditional chemical processes. This innovation is particularly evident in the production of biofuels, biodegradable plastics, and sustainable agricultural solutions, which are in high demand as industries and consumers prioritize environmentally friendly products (MJSM Camacho (2024). [7]). As industrial biotechnology continues to develop, it is likely that even more complex bio-manufacturing processes will emerge, expanding the range of bio-based products and fostering economic growth in new sectors.

The Finnish biotechnology industry is positioned at the forefront of these international trends, benefiting from a robust research and development ecosystem and a focus on sustainability. According to Hermans (2004). [8], Finland's biotech sector is a prime example of how smaller countries can leverage intellectual capital and technological infrastructure to build a competitive advantage in the global biotechnology market. The country's emphasis on bioeconomy aligns with global mega-trends, such as the transition to a circular economy and the development of green technologies. Finland's biotech firms are particularly focused on marine biotechnology, where new products are being developed from biotic resources for pharmaceutical and food applications (N Cascelli (2023). [9]).

Industrial clustering in biotechnology boosts innovation and economic growth. As noted by (Safeena (2020) [10]) clusters of companies, universities, and research institutes create synergies that speed up tech development. They enable idea sharing, access to funding, and easier product commercialization. Clusters also help small biotech firms thrive, driving advances in areas like marine biotech, biofuels, and pharma.

2. OBJECTIVE :

(1) **Assess Biotechnology Industry Growth Trends:** To analyse the growth trajectory of the biotechnology industry in India by identifying the key factors driving its expansion, including technological innovation, increasing healthcare demand, government initiatives, investment

inflows, and the adoption of emerging technologies such as Artificial Intelligence, genomics, and personalized medicine.

(2) **Identify Challenges and Barriers:** To explore the major challenges faced by the biotechnology industry, including regulatory complexities, ethical concerns, high research and development costs, data privacy issues, cybersecurity risks, shortage of skilled professionals, and commercialization barriers, thereby providing a comprehensive understanding of the obstacles affecting industry growth.

(3) **Evaluate Market Dynamics and Stakeholder Perspectives:** To examine the roles and contributions of biotechnology companies, research institutions, healthcare providers, investors, policymakers, and technology providers in shaping the biotechnology ecosystem, while analysing market dynamics, investment patterns, innovation strategies, and competitive developments.

(4) **Apply Strategic Analytical Frameworks:** To utilize analytical frameworks such as SWOC, ABCD, and PESTLE to systematically evaluate the strengths, weaknesses, opportunities, challenges, stakeholder benefits, and external environmental factors influencing the growth, sustainability, competitiveness, and technological transformation of the biotechnology industry.

(5) **Explore Technological Advancements and AI Adoption:** To investigate the adoption and impact of emerging technologies, particularly Artificial Intelligence, machine learning, bioinformatics, genomics, gene editing, and personalized medicine, in enhancing biotechnology research, drug discovery, diagnostics, biomanufacturing, operational efficiency, and healthcare innovation.

(6) **Provide Actionable Recommendations:** To formulate strategic recommendations for biotechnology companies, researchers, healthcare organizations, investors, and policymakers aimed at accelerating innovation, strengthening research and development, promoting responsible AI adoption, improving regulatory support, enhancing workforce capabilities, and ensuring the long-term sustainable growth and global competitiveness of India's biotechnology industry.

3. REVIEW OF LITERATURE :

The literature review plays a crucial role in a scholarly article on industry analysis by offering a thorough basis for comprehending market trends, major challenges, and possible future prospects. It synthesizes existing research, theoretical frameworks, and empirical studies, helping to establish the study's relevance and contextual background. By critically evaluating past studies, a literature review identifies gaps in knowledge, guiding the research toward unexplored or emerging industry dynamics. Additionally, it ensures methodological rigor by highlighting best practices and analytical approaches used in previous studies. Ultimately, a well-structured literature review strengthens the credibility of an industry analysis by grounding its insights in established research and empirical evidence.

3.1 The Biopharmaceutical Biotechnology Sector in India:

This literature review provides an overview of the rapid growth of India's biotechnology and biopharmaceutical sector, highlighting its economic impact and regulatory landscape. As a fast-growing field, biotechnology plays a key role in healthcare, agriculture, and industry. The review covers government initiatives, FDI, R&D, and technological innovations driving progress. It also emphasizes biopharmaceuticals' role in tackling health challenges through vaccines, biosimilars, and personalized medicine.

This review, based on empirical studies and industry reports, underscores India's status as a global biotech hub, with strengths in low-cost drug manufacturing and clinical research. It also identifies key challenges like regulatory issues, IP rights, and infrastructure limitations. Emerging trends such as bioinformatics, gene therapy, and sustainable biomanufacturing are shaping the industry's future, offering direction for further research and strategic planning.

Table 1: Review of some published articles based on keyword: Biotechnology Biopharmaceuticals industry in India

S. No.	Topic	Focus/Outcome	Reference
1	India's biotechnology sector is rapidly evolving	A comparison of India's health biotechnology publications and USPTO patents from 1991 to 2002 highlights the	Nandini K Kumar, Uyen

	and increasingly driven by leadership	country's growing innovation in science and commercial potential. Science-Metrix data show a steady rise in publications, while USPTO records reveal a similar increase in patents. Both peaked in 2002.	Quach, (2004). [11]
2	Building Biopharmaceutical Capabilities in India: Insights from a Symposium Report	The biopharmaceutical industry is transitioning toward advanced cell and gene therapies, which demand higher drug quality standards, reduced manufacturing failures, and accelerated time-to-market. In response USP, DBT India, and CII organized a symposium to evaluate the biotech and pharmaceutical sectors in India and other developing nations. Experts emphasized the importance of cultivating a skilled workforce, fostering public-private partnerships, advanced cutting-edge technologies, advancing novel biologics, implementing supportive policy frameworks.	Annu Uppal, Ranjan Chakrabarti, (2021). [12]
3	Indian biosimilars and vaccines at a turning point: Aiming to Replicate the Success of Generic Pharmaceuticals	India is transitioning from a focus on generics to the production of biologics and biosimilars, currently accounting for 20% of global generics supply and 62% of vaccine production. Companies like Biocon and Dr. Reddy's lead in biosimilar development, with major contributions during COVID-19. Despite progress, challenges remain in innovation, collaboration, and IP rights. Strengthening partnerships, skills, and IP awareness is key to future growth.	Sunita Panda, Puneet Kumar Singh, (2023). [13]
4	Opportunities for Business Model Innovation in the Biopharmaceutical Industry: A Systematic Review	Interest in business model innovation within the biopharmaceutical industry has increased, driven by innovation challenges and economic pressures. A review of 305 academic studies from 1976 to 2013 identified five key areas driving innovation: External Orientation, Learning Capabilities, Cluster Participation, Skilled Management Teams, and Organizational Controls. The study offers insights for advancing innovation in biopharma and serves as a reference for related sectors.	James B Downs, Vivek Velamuri (2016). [14]
5	Biotechnology business models: An Indian perspective	Biotechnology lacks a standard business model, showing high adaptability in value creation and revenue strategies. This flexibility helps firms navigate economic shifts. In India, biotech companies focus on biopharmaceuticals and related services. This paper explores their business models, strategies, and key growth challenges.	viren Konde (2009). [15]
6	A comprehensive review and meta-analysis of recent	Plant-based secondary metabolites are cost-effective sources for medicines. Advances in genetic engineering, like molecular	Sandip Debnath, Dibyendu Seth, (2024). [16]

	advancements in biotechnology for plant virus research, along with major achievements in human health and the pharmaceutical sector	pharming, use plant viruses (VLPs and VNPs) to produce therapeutic proteins. With bioinformatics, HTS, and NGS, metagenomic studies now help identify virus genomes for drug development. The article shows how biotech is driving plant virus-based pharma research.	
7	The rise of biopharmaceutical innovators in China, India, Brazil, and South Africa as emerging global competitors and strategic collaborators	Biopharmaceutical innovation has significantly impacted global health and the economy, with developed nations leading. However, emerging markets like China, India, Brazil, and South Africa are rapidly progressing. This paper explores how entrepreneurs in these countries overcome challenges, aided by state support and global partnerships, to compete internationally.	Rahim Rezaie, Anita M McGahan, (2012). [17]
8	India's Biotechnology Sector: Strengths, Challenges, Solutions, and Future Prospects	The Department of Biotechnology, established in 1986, helped build India's scientific workforce and R&D in life sciences. The private sector supported this by offering affordable vaccines and healthcare. Despite progress, innovation challenges persist. The 2007 National Biotechnology Development Strategy aimed to improve collaboration, and many goals are being achieved with strong government backing. India is now reshaping its science sector with promising results.	Sribhargava Natesh, Maharaj Kishan Bhan (2009). [18]
9	R&D strategies, knowledge base and market sales of Indian biopharmaceutical firms	This paper explores three key questions about Indian pharmaceutical firms using biotechnology in marketing, production, or research: (i) the impact of skilled labour on sales, (ii) R&D strategy elements as substitutes or complements, and (iii) traits of firms adopting biotech research. The findings indicate that skilled labour enhances sales; internal R&D and foreign collaborations act as substitutes, whereas patents and publications function as complementary assets. Biotech-focused firms are typically younger and pursue aggressive learning strategies.	Shyama V Ramani (2002). [19]

3.2 The Genomics and Precision Medicine Segment of the Biotech Industry:

Research in genomics and personalized medicine has transformed modern healthcare through technological advancements. Technologies such as high-throughput DNA sequencing, bioinformatics, and machine learning have advanced the identification of genetic markers and the creation of targeted therapies. Personalized medicine leverages this data to customize treatments based on an individual's genetic makeup, enhancing effectiveness and minimizing side effects. Technologies like CRISPR have enabled precise gene editing for treating genetic disorders. Additionally, innovations in synthetic biology and bioprocess automation have boosted the large-scale production of personalized drugs, making advanced healthcare more efficient and accessible.

Table 2: Review of some published articles based on keyword: Genomics and Personalized Medicine biotechnological industry

S. No.	Topic	Focus/Outcome	Reference
1	A Review of Innovations in Genomics and Big Data Analytics for Personalized Medicine and Healthcare	Big data is revolutionizing healthcare by enabling large-scale, data-driven research, especially in precision medicine. Integrating omics and clinical data presents both challenges and opportunities. New algorithms now factor in genetic variability to support personalized treatments. This review highlights the role of big data analytics—such as machine learning, genomic models, and data mining—in advancing personalized healthcare, while also noting key implementation challenges.	Mubashir Hassan, Faryal Mehwish Awan, Anam Naz, (2022). [20]
2	Personalized Diagnostics and Biosensors: A Review of the Biological and Technological Foundations for Personalized Medicine	Genomics, proteomics, and metabolomics are deepening our understanding of health and improving personalized medicine through better diagnostics and drug development. For practical use, point-of-care devices must be cost-effective alternatives to lab tests. Advanced sensors can now detect nucleic acids, proteins, metabolites, and pathogens, expanding diagnostic options. While these tools are becoming more sensitive and efficient, the main challenge remains their widespread adoption and real-world impact on patient care.	Minhaz Uddin Ahmed, Ishtiaq Saaem, Pae C Wu, (2014). [21]
3	Personalized medicine and cancer	Cancer remains a major cause of death in the U.S., with over 1.5 million new cases and 500,000 deaths in 2010. Advances in genomics have improved personalized medicine, using genetic and patient-specific data to guide cancer prevention and treatment. Molecular profiling and companion diagnostics help tailor therapies and assess risks. This paper reviews recent progress, challenges, and future prospects in personalized cancer care.	Mukesh Verma, (2012). [22]
4	Biotechnology in Personalized Medicine: Emerging Trends and Future Perspectives	Personalized medicine is changing healthcare. It tailors treatments to individual genetic, environmental, and lifestyle factors. Biotechnology drives this shift with advanced tools. These include genomic sequencing, gene editing, and biomarkers. This article reviews key trends in biotechnology shaping personalized medicine. It also explores future directions like AI integration and bioinformatics advancements. Ethical and regulatory challenges are discussed as well. The goal is to show biotechnology's impact on healthcare and patient outcomes	Muhammad Imran, (2024). [23]

5	Human genomics projects and precision medicine	The completion of the Human Genome Project in 2001 advanced precision medicine, enabling genome-based diagnosis and treatment. While many genomic projects are ongoing, data privacy in cloud computing remains a concern. P4 medicine (predictive, preventive, personalized, participatory) presents new opportunities and challenges. This review highlights current sequencing technologies and examples of genomics in clinical care.	Fernando Carrasco-Ramiro, Ramón Peiró-Pastor, (2017). [24]
6	Personalized medicine: progress and promise	Personalized medicine is an emerging field that customizes healthcare using a person's clinical, genetic, and environmental data. It involves multidisciplinary teams and tools like clinical decision support systems to apply molecular insights for better preventive care. With access to human genome data, providers can now create personalized care plans at every disease stage, shifting from reactive to proactive, patient-specific treatment approaches.	Isaac S Chan, Geoffrey S Ginsburg, (2011). [25]
7	Precision and Personalized Medicine: Enhancing the Management of Cardiovascular and Neurodegenerative Diseases Through Genomic Approaches	Rising life expectancy increases healthcare costs due to aging and chronic diseases. Precision medicine helps by enabling early detection and targeted treatment, especially for heart and brain conditions. AI and biomedical research improve understanding of health factors. This boosts prevention, care, and lowers costs while improving quality of life.	Oriana Strianese, Francesca Rizzo, Michele Ciccarelli, (2020). [26]
8	Personalized Medicine and the Impact of Human Genetic Diversity	This article explores human genetic diversity and its role in disease risk and evolution, from early theories to modern tools like GWAS and next-generation sequencing. It covers population-specific diseases like sickle cell anaemia and Tay-Sachs, and how genetic variants influence treatment, such as in hepatitis C. It emphasizes the ongoing importance of genetic diversity in medical and personalized medicine.	Yi-Fan Lu, David B Goldstein, Misha Angrist, (2014). [27]
9	Genomics and the reimagining of personalized medicine	This book traces the evolution of personalized medicine from 20th-century biomedicine to pharmacogenomics and personal genomics. It contrasts earlier focus on patients' social experiences with the recent emphasis on genetics in disease and treatment. The book discusses how genetic information shapes personalized medicine, highlighting gaps between current science and future potential. It also examines the impact on healthcare economics, delivery, and societal views, offering insights for medical sociology and health policy.	Richard Tutton Routledge, (2016). [28]

3.3 Future Outlook of biotechnology industry:

The biotechnology industry has a bright future, fueled by innovations in genomics, artificial intelligence (AI), and automation. AI and machine learning are set to revolutionize drug development, personalized medicine, and genetic engineering by improving data analysis and enabling more precise, tailored treatments. Technologies like CRISPR gene editing, synthetic biology, and automated bioprocessing will further enhance accuracy, scalability, and efficiency in biotech applications. Although the industry faces challenges such as complex regulations, data security concerns, and a lack of skilled professionals, increasing investments in research and development, along with global collaborations, are expected to drive significant growth and improvements in healthcare delivery.

Table 3: Review of some published articles based on keyword: Future Outlook of biotechnology industry

S. No	Topic	Focus/Outcome	Reference
1	Marine Biotechnology: Challenges and Emerging Market Trends in utilizing Biotic Resources for Industrial Pharmaceutical and Food Applications.	Biotechnology supports sustainable use of marine resources but faces cognitive and technical challenges. A review of global studies shows strong growth in blue biotechnology, especially in pharma and food. Research doubled from 2010 to 2019, with focus on molecular techniques. Growth in omics and bioinformatics shows new trends. Better methods for cultivation and extraction are key to bringing marine products to market.	Sara Daniotti, Ilaria Re (2021). [29]
2	Microalgae-Derived Pigments: A Decade of Bibliometric Analysis and Insights into Industry and Market Trend	Microalgae are emerging as a key sustainable source of natural pigments. This review highlights the most promising pigments and microalgae species, drawing on a decade of bibliometric analysis, patent data, and market trends. Increasing investments in microalgae cultivation and pigment extraction, especially phycocyanin from Spirulina, are driving the growth and consolidation of the microalgal pigment market. This trend suggests that natural pigments may increasingly replace synthetic ones in the future.	Samara C Silva, Isabel CFR Ferreira, (2020). [30]
3	Microalgal biofuel revisited: an informatics-based analysis of developments to date and future prospects	Microalgae are a promising source of biofuel, with major research and patent growth from 2006 to 2011. However, high costs and limited basic research led to a decline after 2012. Future efforts aim to improve understanding and technology, offering potential economic and social benefits. This review guides future research and policy.	Hui Chen, Tian Qiu, Junfeng Rong, Chenliu He, (2015). [31]
4	Technological prospection of microalgae-based biorefinery approach for effluent treatment	The microalgae-based biorefinery with effluent treatment (MBBET) offers a cost-effective way to produce biomass and products in a circular bioeconomy. This review uses patent data to highlight trends and gaps in the technology. MBBET shows potential to tackle global water, food, and energy issues, with scope for future improvements.	Luiggi Cavalcanti Pessôa, Kricelle Mosquera Deamici, (2021). [32]
5	Analysis of scientific research driving	A bibliographic database of 79,020 scientific papers on “microalgae” or “phytoplankton” from global research institutions, especially in	Judith Rumin, Elodie Nicolau, (2020). [33]

	microalgae market opportunities in Europe	Europe, was analyzed using Orbit Intellixir software. The study identified six key market opportunities—biofuels, bioplastics, biofertilizers, nutraceuticals, pharmaceuticals, and cosmetics—and two rapidly evolving technologies: microalgae harvesting/extraction and genetically modified microalgae. This analysis provides an updated overview of scientific trends driving microalgae markets.	
6	Biotechnology and the bioeconomy—Towards inclusive and sustainable industrial development	Biotechnology can help transform developing countries into industrialized ones by supporting bio-based industries, ensuring sustainability, and reducing environmental harm. In agribusiness, it can improve farming inputs, mechanization, food processing, packaging of perishable goods, and food safety, leading to a more efficient and sustainable sector.	Yvonne Lokko, Marc Heijde, Karl Schebesta, Philippe Scholtès, (2018). [34]
7	Bacteriophages and their implications on future biotechnology	Bacteriophages, natural predators of bacteria, are gaining importance in biotechnology as alternatives to antibiotics, especially against resistant strains. They are also used in agriculture, petroleum biocontrol, vaccine delivery, bacterial detection, and protein display. Their diversity and ease of manipulation make them valuable tools in research and therapeutics. This review supports efforts to advance phage use in various biotech fields.	Irshad Ul Haq, Waqas Nasir Chaudhry, (2012). [35]
8	Bioeconomy a review of the literature	The bioeconomy has gained attention as a solution to global challenges, but its definition remains unclear. This paper clarifies the term by analysing academic literature and finds the field divided, mostly focused on natural and engineering sciences. It identifies three main perspectives: the bio-technology vision (biotech research and commercialization), the bio-resource vision (processing biological materials and value chains), and the bio-ecology vision (sustainability, energy, biodiversity, and soil health).	Markus M Bugge, Teis Hansen, (2016). [36]
9	Production technologies, current role, and future prospects of biofuels feedstocks: A state-of-the-art review	Overuse of fossil fuels and carbon emissions have boosted interest in renewable energy like biofuels. These include biogas, biodiesel, bioethanol, and more, made from crops, waste, or microalgae. Third-generation biofuels from microalgae offer better yields and lower emissions but need more resources. This paper reviews their environmental and economic sustainability.	Arianna Callegari, Silvia Bolognesi, Daniele Cecconet, (2020). [37]
10	The development history and prospects of biomass-based insulation	Thermal insulation is key for energy savings in buildings, with bio-based insulations from agro and forest residues growing rapidly. This study reviews 144 papers to highlight global trends in bio-insulation research, covering its history, geographic focus, biomass types, methods,	LiFang Liu, HongQiang Li, Andrea Lazzaretto, Giovanni Manente, (2017). [38]

	materials for buildings	manufacturing, and material properties. It identifies research gaps and suggests improvements like better material selection, innovative treatments, and enhanced testing to advance bio-insulation use in construction.	

3.4 Summary of Review:
The future outlook of the biotechnology industry, based on a review of various literatures, suggests continued growth driven by advancements in genetic engineering, personalized medicine, and biopharmaceuticals. Emerging technologies such as crisper, aid-driven drug discovery, and synthetic biology are expected to enhance efficiency and innovation. Increased investment in biotech startups, supportive regulatory frameworks, and rising demand for sustainable solutions in agriculture and healthcare will further propel the industry. However, challenges such as ethical concerns, high R&D costs, and regulatory uncertainties could impact its trajectory. Overall, the sector remains poised for transformative developments with significant economic and societal implications.

4. RESEARCH AGENDAS & ISSUES OF INDIAN BIOTECHNOLOGY PRACTICES :

Here are some research agenda suggestions for an industry analysis paper on the biotechnology industry related to the "Adoption and Impact of Al in Biotechnology Industry Operations in India":

(1) Historical Evolution & Regulatory Developments in Al-Driven Biotechnology:

• **Agenda 1:** Evolution of Al in Biotechnology - A historical review of Al adoption in the Indian biotechnology sector, including advancements from manual research methodologies to Al-driven automation in drug discovery, genomics, and bioinformatics.

• **Agenda 2:** Regulatory Framework for Al in Biotechnology - Analysis of government policies, ethical guidelines, and biotechnology regulations influencing Al deployment in drug development, genetic engineering, and clinical trials.

• **Agenda 3:** Al's Role in Healthcare Biotechnology - Evaluating Al-driven innovations in diagnostics, personalized medicine, and biopharmaceutical development in India.

(2) Present Role of AI in India's Biotechnology Sector:

• **Agenda 4:** Al Applications in Biotechnology Operations Assessing Al's role in genomic sequencing, precision medicine, bioinformatics, agricultural biotech, and biomanufacturing.

• **Agenda 5:** Industry Perceptions of Al in Biotechnology - Exploring perspectives of biotech companies, researchers, and investors on Al-driven solutions in biotechnology.

• **Agenda 6:** Comparative Study of Al Adoption in Indian Biotech Firms Analysing Al integration across pharmaceutical companies, a gritech start-ups, research institutions, and healthcare-focused biotech firms in India.

(3) SWOC Assessment of Artificial Intelligence in the Biotechnology Sector:

• **Agenda 7:** Strengths of Al in Biotechnology - Identifying Al's competitive advantages in biotechnology, such as increased efficiency in drug discovery, precision agriculture, and biomedical research.

• **Agenda 8:** Weaknesses & Challenges in Al Implementation - Evaluating barriers like data privacy concerns, high costs, lack of Al expertise, and regulatory challenges in the Indian biotech industry.

• **Agenda 9:** Opportunities for Al in Biotechnology - Exploring potential areas where Al can enhance clinical research, vaccine development, synthetic biology, and regenerative medicine.

• **Agenda 10:** Challenges in Al Adoption Investigating legal, ethical, and infrastructural constraints, including concerns related to Al in genetic data handling and algorithmic biases in research.

(4) ABCD Analytical Structure:

• **Agenda 11**: Advantages for Biotech Companies & Research Institutions Examining how Al improves R&D efficiency, accelerates drug discovery, and optimizes clinical trials.

• **Agenda 12**: Benefits for Healthcare & Agricultural Sectors - Assessing Al's role in enhancing disease diagnosis, vaccine research, and precision farming.

• **Agenda 13:** Constraints in Al Implementation - Identifying roadblocks such as high costs, lack of skilled Al professionals, and limitations in data standardization.

• **Agenda 14**: Disadvantages for Workforce & Society - Investigating workforce concerns about job displacement, ethical issues in genetic engineering, and potential Al misuse in biotech research.

(5) PESTEL Evaluation of Artificial Intelligence in the Biotech Industry:

• **Agenda 15:** Political & Legal Factors Studying government policies, Al regulations, and intellectual property laws affecting Al adoption in biotechnology.

• **Agenda 16:** Economic Factors Evaluating how Al contributes to cost reduction, revenue growth, and investment trends in the biotech industry.

• **Agenda 17:** Social & Ethical Considerations – Analysing Al's role in personalized medicine, genetic privacy concerns, and bioethical dilemmas.

• **Agenda 18:** Technological Advancements - Examining Al's impact on synthetic biology, CRISPR technology, Al-powered drug discovery, and healthcare innovations.

• **Agenda 19:** Environmental and Sustainability Considerations – Investigating the Role of AI in Promoting Sustainable Farming, Advancing Biofuel Technologies, and Developing Environmentally Friendly Biotech Innovations.

(6) Strategic Advice for Decision-Makers, Biotech Organizations, and Investment Stakeholders:

• **Agenda 20:** Developing an AI Policy Roadmap for Indian Biotechnology – Crafting policy recommendations to ensure ethical use of AI, promote investment incentives, and establish regulatory structures for AI-powered biotech innovations.

• **Agenda 21:** Strategic Investments in AI-Powered Biotechnology – Exploring potential AI investment avenues for biotech startups, pharmaceutical companies, and venture capital investors.

• **Agenda 22:** Preparing the Workforce for AI Integration – Designing training initiatives to upskill professionals and embed AI capabilities within biotechnology research and development.

• **Agenda 23:** Collaboration Between Biotech Firms & Al Startups Exploring partnerships between biotech companies, Al innovators, and academic institutions for Al-driven research.

• **Agenda 24:** Framework for Risk Management – Establishing regulatory guidelines and cybersecurity measures to support responsible and secure implementation of AI in biotechnology.

These research agendas support the goals of an industry analysis paper examining the adoption and effects of AI in India's biotechnology sector. This study will provide meaningful insights into AI-driven changes in biotechnology by examining technological innovations, stakeholder viewpoints, regulatory considerations, and strategic guidance.

5. METHODOLOGY :

This study adopts an exploratory and analytical research methodology based exclusively on secondary data to examine the trends, market dynamics, technological advancements, and future outlook of the biotechnology industry. Information was collected from peer-reviewed journal articles, government publications, industry reports, company reports, books, and other credible online sources. The study employs qualitative analytical techniques supported by strategic frameworks, including SWOC (Strengths, Weaknesses, Opportunities, and Challenges), ABCD (Advantages, Benefits, Constraints, and Disadvantages), and PESTLE (Political, Economic, Social, Technological, Legal, and Environmental) analyses to evaluate both the internal capabilities and external business environment of the biotechnology industry. In addition, the study analyses the adoption and impact of Artificial Intelligence and other emerging technologies from the perspectives of key stakeholders, including biotechnology companies, researchers, healthcare organizations, policymakers, investors, and consumers, to provide a comprehensive assessment of the industry's current status and future growth prospects (Costa et al. (2004). [39]).

6. THE INDIAN BIOTECHNOLOGY INDUSTRY: PAST AND PRESENT :

6.1 Historical Progress:

Biotechnology has evolved from ancient drug discoveries by civilizations like the Babylonians, Egyptians, and Greeks to modern fields such as genomics, proteomics, and bioinformatics. Pharmaceuticals have shifted from empirical methods to advanced techniques using genetically modified organisms. While food tech has grown through mechanization, the rising demand for bioengineers now exceeds supply. Emerging biotech complexities call for updated curricula and interdisciplinary collaboration, along with improved communication between scientists and the public to address concerns and ensure access to reliable health and food resources (Hulse (2004). [40]).

6.2 Types of Biotechnology:

The Indian biotechnology sector can be broadly classified into four primary types:
(1) Red Biotechnology (Healthcare and Pharmaceuticals): Red biotechnology focuses on medical and pharmaceutical applications, such as drug development, gene therapy, and diagnostics.
(2) Sustainable Biotechnology (Agricultural Biotechnology): Green biotechnology involves using biological processes for agricultural applications such as genetically modified (GM) crops, plant-based medicines, and sustainable farming practices.
(3) White Biotechnology (Industrial Biotechnology): White biotechnology involves using biotechnology for industrial applications such as biofuels, biodegradable plastics, and enzymes for manufacturing processes
(4) Blue Biotechnology (Marine Biotechnology): Blue biotechnology involves utilizing marine resources for various industrial purposes (Festel (2010). [41]).

6.3 Growth Through Horizontal and Vertical Integration:

Biotechnology companies have pursued both horizontal and vertical growth strategies to strengthen their market presence and broaden their range of services.
(1) Industry Expansion: Biotechnology firms have expanded their global footprint by setting up research and production centres across various regions and nations. For instance, companies like Biocon have expanded their operations both within India and internationally, entering markets in the US and Europe to cater to global healthcare needs
(2) Vertical Expansion: Biotechnology companies have expanded across multiple stages of the biotech value chain, ranging from R&D to manufacturing and bringing products to market. This vertical expansion enables biotech companies to control more aspects of the production and distribution process, increasing efficiency and profitability.
Both horizontal and vertical expansions in the biotechnology industry enable companies to grow their footprint, diversify their offerings, and cater to a broader range of customer needs, similar to the strategies employed by banks in the financial sector (Zambon (2019). [42]).

6.4 Customer-Focused Support:

To improve customer experience and keep pace with technological progress, biotech companies have introduced a range of client-focused initiatives:
(1) Personalized Healthcare Solutions: Biotech companies provide customized therapies and treatments tailored to an individual's genetics, environment, and lifestyle. For instance, organizations such as Geneva Healthcare utilize genetic testing to design patient-specific treatments, enabling a more precise and effective healthcare approach.
(2) Digital Health Platforms: The use of digital health tools, including telemedicine and mobile applications, has increased the accessibility and convenience of healthcare services for patients. Biotech companies are integrating digital platforms to monitor patients remotely, offer virtual consultations, and provide real-time updates on treatment progress.
(3) Patient Education and Awareness Programs: Biotechnology companies are increasingly focusing on educating patients about medical conditions, treatments, and advancements in biotechnology. Initiatives such as workshops, online courses, and awareness campaigns aim to empower patients with knowledge, enabling them to make informed decisions about their healthcare.

These efforts aim to strengthen the relationship between biotechnology firms and their customers by offering more accessible, personalized, and educational services, ultimately enhancing the overall healthcare experience (Hotha (2023). [43]).

6.5 Strategic Acquisitions:

The Indian biotechnology industry has increasingly focused on customer-centric services, driven by the need for personalized healthcare solutions, improved access to diagnostics, and more effective agricultural products. Companies have begun using artificial intelligence (AI), machine learning (ML), and data analytics to enhance product offerings. For instance, healthcare providers are now offering personalized medicine and gene therapy, tailored to individual genetic profiles (Danzon et al. (2007). [44]).

Additionally, agricultural biotechnology firms have shifted towards providing farmers with more accessible and sustainable agricultural solutions, such as seeds resistant to drought or pests. Companies have also developed easy-to-use diagnostic kits for rural areas, ensuring better access to healthcare for under-served populations.

6.6 Corporate Social Responsibility (CSR) Activities:

Biotechnological Corporate Social Responsibility (CSR) Activities:

(1) Healthcare Access and Affordability: Biotechnology companies are involved in initiatives aimed at improving access to affordable healthcare, including the development of low-cost medications and providing support to under-served communities.

(2) Environmental Sustainability: Biotech firms focus on environmentally friendly practices, such as reducing waste, using renewable resources, and developing green technologies, including bio-based alternatives to traditional chemical processes.

(3) Education and Skill Development: Numerous biotech firms invest in education and skill-building initiatives, especially in STEM areas, to foster knowledge and innovation in local communities.

(4) Research for Public Health: Biotechnology firms play a vital role in public health by creating vaccines, therapies, and diagnostic technologies aimed at tackling worldwide health issues such as pandemics and long-term diseases.

These corporate social responsibility efforts highlight the biotechnology industry's dedication to ethical responsibility and sustainable growth. The biotech field has progressed considerably over time, integrating cutting-edge technologies and tackling worldwide health and environmental issues. Centred on innovation, public well-being, sustainability, and community advancement, the sector remains vital in creating a healthier and more sustainable future.

7. TECHNOLOGICAL ADVANCEMENTS IN INDIA’S BIOTECHNOLOGY SECTOR :

The biotechnology industry in India has emerged as a key contributor on the global stage, especially in areas such as biopharmaceuticals, genomics, personalized healthcare, and cutting-edge technologies. With a rapidly evolving market and a growing demand for innovative healthcare solutions, India has positioned itself as a key destination for biotechnological advancements. This overview offers a detailed examination of the technological progress in biopharmaceuticals, genomics, personalized medicine, future prospects, and the integration of emerging technologies within India’s biotechnology industry.

7.1 Technological Biopharmaceuticals in India:

The Indian pharmaceutical and biopharmaceutical sectors have traditionally been seen as technologically stagnant, with low R&D investments, a focus on copying on-patent drugs (if a novel process is found), and manufacturing off-patent generic drugs. The research identifies at least three different selection environments and types of learning that contributed to firms' capabilities. These findings suggest that while national policies like patent laws are important, they don't fully explain the sector's progress. The study also highlights the need for broader discussions on public health medicines and technological learning in developing countries (Srinivas (2004). [45]).

7.2 Genomics and Personalized Medicine:

Pharmaceutical biotechnology is growing rapidly, with 2005 marking a record year for FDA approvals, including 21 biopharmaceutical products. Techniques from molecular biology, such as recombinant

DNA technology and hybridoma techniques for monoclonal antibodies, have been key in developing current therapeutic agents. These innovations are revolutionizing drug development, diagnostics, and medical devices, making the process more efficient despite its competitive and costly nature. Numerous technologies are currently applied in clinical trials, with their complete influence on the future of medicine yet to be fully realized (Sindelar (2024). [46]).

7.3 India's potential for personalized medicine:

Affordable and accessible healthcare remains a major challenge in many countries, but advancements like personalized medicine (PM) offer potential solutions. This study explores the adoption of PM in India using the sectoral innovation system framework, analysing government initiatives and research trends through Web of Science data. It highlights India's changing healthcare landscape, focusing on research collaboration, sectoral boundaries, and policy efforts. Based on identified gaps, the study suggests a comprehensive policy framework to better integrate PM into India's healthcare system (Goyal & Yennappu (2023). [47]).

7.4 Future Outlook:

Global efforts toward decarbonization and sustainability have increased the demand for bio-based chemicals and fuels, particularly in the biodiesel industry. However, the production of glycerol as a by-product presents challenges in realizing a glycerol-based biorefinery. This review discusses glycerol-assimilating microbes, their metabolic pathways, and genetic issues, while exploring biotechnological advances such as microbial bioprospecting, mutagenesis, and metabolic engineering that address these challenges (Daud (2004). [48]).

7.5 Market growth:

Biotechnology is increasingly used to produce chemicals, polymers, and high-value products like specialty chemicals and pharmaceuticals. In 2010, global biotech sales reached €92 billion, with projections of €228 billion by 2015 and €515 billion by 2020. Key market areas include biopolymers and active pharmaceutical ingredients. While multinationals lead commercialization, small and medium enterprises drive innovation but struggle with business models and funding. Though investors have been cautious, growing awareness of biotechnology's potential may attract more investment.

7.6 Innovation in Biotechnology:

This study centres on evaluating the financial value of a company's knowledge assets and the benefits gained from innovation within the biotechnology industry, where research and development (R&D) is vital to product success. The biotech sector is heavily focused on research, with pharmaceutical product development progressing through specific phases that enable accurate assessment of results. The paper provides up-to-date R&D data and estimates the private returns from innovation and product creation. It concludes that the financial market recognizes the value of drugs in development, expecting the innovative knowledge behind these projects to lead to marketable products in the future.

8. SWOC ANALYSIS OF INDIAN BIOTECHNOLOGY INDUSTRY :

The industry's SWOC analysis reveals strengths such as innovation and growth potential, but also highlights weaknesses like limited capital market presence and high investment risks. Opportunities lie in expanding foreign investment and advancing research, while threats include regulatory challenges and competition from global biotech players. Despite these challenges, the government is revising policies to encourage sector growth and attract foreign investment [49-58].

8.1 Strengths in the Biotechnology Industry:

Table 4: Strengths in the Biotechnology Industry

S. No.	Key Strengths	Description
1	**Accelerated Drug Discovery & Development (Pharmaceutical Perspective)**	AI-driven simulations and predictive modelling reduce drug discovery time and costs; enables faster target identification.

2	**Personalized Medicine & Tailored Treatments (Healthcare Perspective)**	AI analyzes genetic and clinical data to tailor treatments and improve patient outcomes.
3	**Cost Reduction in R&D (Biotech Companies Perspective)**	AI-driven automation reduces manual effort; predictive analytics minimize failed trials, optimizing R&D investment.
4	**Data-Driven Crop Biotechnology (Agricultural Perspective)**	AI improves crop yield, disease resistance, and enhances precision agriculture and soil monitoring.
5	**Enhanced Biomanufacturing Processes (Industrial Perspective)**	AI optimizes bioprocessing and ensures quality control in vaccine and enzyme production.
6	**Faster Disease Surveillance & Prediction (Public Health Perspective)**	AI predicts and controls disease outbreaks through epidemiological data analysis and early warning systems.
7	**Genomics & Proteomics Advancements (Scientific Research Perspective)**	AI accelerates gene sequencing and biomarker discovery; enables protein structure prediction for drug design.
8	**Efficient Clinical Trials (Regulatory & Ethical Perspective)**	AI identifies suitable participants, reduces bias, and accelerates approval processes through predictive analytics.
9	**Intelligence Bioinformatics Solutions (Technology Perspective)**	AI tools handles large biological data sets for genome annotation and understanding novel pathways.
10	**Job Creation & Upskilling Opportunities (Economic Perspective)**	AI increases demand for skilled professionals; promotes workforce development through training programs.

8.2 Weaknesses in the Biotechnology Industry:

Table 5: Weaknesses in the Biotechnology Industry

S .No.	Key Weaknesses	Description
1	**High cost of infrastructure**	Biotechnology R&D requires significant capital for labs, equipment, and AI integration.
2	**Limited AI Readiness in Workforce**	There is a shortage of professionals skilled in both biotech and AI/ data analytics.
3	**Data Privacy & Ethical Concerns**	Genetic and health data usage raises ethical, legal, and privacy issues.
4	**Inconsistent Data Quality**	AI models require large, clean datasets which may be unavailable or poorly curated in India.
5	**Lack of Standardisation**	Absence of uniform protocols in data collection, analysis, and regulatory practices.
6	**Low Commercialization Rate of Research**	Many biotech innovations struggle to reach market due to long approval process or lack of funding.
7	**Long Product Development Cycles**	Drug and therapy development can take over a decade to reach the market.
8	**Limited Skilled Talent**	Shortage of professionals with specialized biotech knowledge and expertise.
9	**Dependence on Government Funding**	Many biotech firms rely heavily on grants or subsidies, limiting independence.
10	**Scalability Issues**	Transitioning from lab to mass production is often challenging and costly.

8.3 Opportunities in the Biotechnology Industry:

Table 6: Opportunities in the Biotechnology Industry

S. No.	Key Opportunity	Description
1	**Personalized Medicine Growth**	Rising demand for tailored therapies based on genetics and biomarkers.
2	**AI and Bioinformatics Integration**	AI enhances drug discovery, diagnosis, and data analysis.
3	**Agricultural and Environmental Biotech**	Opportunities in crop yield improvement, waste treatment, and sustainability.
4	**Strategic Collaborations**	Partnerships with big pharma and tech companies accelerate progress.
5	**Emerging Market Expansion**	Developing countries have growing biotech needs and lower competition.
6	**Government Incentives**	Supportive policies and funding from health and innovation departments.
7	**Biologics and Biosimilars Demand**	Increasing interest in biologic drugs and their more affordable alternatives.
8	**Gene Editing Technologies**	Tools like CRISPR open new possibilities in treatment and diagnostics.
9	**Remote and Digital Health Integration**	Digital platforms improve patient monitoring and clinical trials.
10	**Pandemic Preparedness**	Global focus on vaccine and antiviral development has opened new funding flows.

8.4 Challenges in the Biotechnology Industry:

Table 7: Challenges in the Biotechnology Industry

S. No.	Key Opportunity	Description
1	**Regulatory Hurdles**	Strict and lengthy approval processes delay market entry.
2	**Ethical and Social Concerns**	Gene editing and cloning raise moral, ethical, and legal questions.
3	**Intellectual Property Conflicts**	Patent disputes can stall innovation and lead to costly litigation.
4	**Clinical Trial Complexity**	Trials are expensive, time-consuming, and prone to failure.
5	**Pricing and Accessibility Pressures**	High treatment costs lead to public criticism and payer push back.
6	**Cybersecurity Risks**	Growing digital infrastructure requires strong data protection.
7	**Rapid Tech Evolution**	Constant innovation makes some technologies obsolete quickly.
8	**Global Supply Chain Disruptions**	Manufacturing and distribution rely on fragile global networks.
9	**Talent Retention**	High competition makes it hard to ratain specialized talent.
10	**Geopolitical Instability**	Trade restrictions and political issues affect cross-border collaboration.

Thus, the Indian biotechnology industry presents significant opportunities driven by government support, increasing demand for bio-based products, and advancements in research and technology. However, it also faces challenges such as limited access to capital, complex regulatory frameworks, and a shortage of skilled workforce. Although the industry shows significant growth prospects, overcoming these obstacles is crucial to fully leverage the opportunities and ensure long-term advancement in the global biotechnology sector.

9. EVALUATION OF THE INDIAN BIOTECHNOLOGY INDUSTRY'S TECHNOLOGY ADOPTION, FOCUSING ON AI: AN ABCD ANALYSIS FROM STAKEHOLDERS' PERSPECTIVES :

9.1 Technology Adoption in the Indian Biotechnology Sector with a Focus on AI:

The Indian biotechnology industry has undergone a major shift by embracing technology, where Artificial Intelligence (AI) has been key in improving operational efficiency and enhancing customer experience [59-78].

(1) Artificial Intelligence in Pharmaceutical Research and Development:

- **Speedier Pharmaceutical Development**: AI is accelerating medication discovery by analysing extensive datasets, pinpointing potential compounds, and forecasting their effectiveness prior to clinical testing. Indian biotech companies are leveraging AI to minimize the high cost and lengthy timelines traditionally associated with drug development.
- **Machine Learning Models:** By using machine learning algorithms, researchers can simulate molecular interactions and optimize compounds for specific biological targets. This has opened new avenues for the development of personalized drugs and biologics, CD especially for diseases like cancer, diabetes, and cardiovascular disorders.
- **Collaborations with AI Startups:** Several Indian biotech firms are collaborating with AI startups to streamline research processes. These collaborations facilitate faster data analysis, pattern recognition, and predictive modelling, making drug discovery more efficient.

(2) AI in Precision Medicine and Personalized Healthcare:

- **Genomics and AI Integration:** AI is revolutionizing precision medicine in India by examining genomic data to detect genetic differences that affect disease susceptibility and how patients respond to treatments. Indian biotechnology companies are incorporating AI to better understand genetic profiles and provide personalized treatment options.
- **Improved Patient Outcomes:** AI algorithms analyse patient information including genetics, lifestyle, and environmental influences to develop personalized treatment plans. This helps in reducing adverse drug reactions and improving overall treatment outcomes, particularly in complex diseases like cancer and genetic disorders.
- **Collaborative Efforts in Healthcare:** India's growing healthcare ecosystem is driving collaborations between biotech firms, hospitals, and tech companies, enabling AI to analyse large volumes of health data for predictive analytics, early disease detection, and treatment planning.

(3) AI in Diagnostics and Healthcare Delivery:

- **Medical Imaging and Diagnostics:** AI technologies are increasingly used in medical diagnostics, especially for analysing medical images such as CT scans, X-rays, and MRIs. These artificial intelligence models can identify abnormalities, including tumor, more accurately and at earlier stages, leading to better diagnostic results.
- **Remote Healthcare Solutions:** India's vast population and rural areas are benefiting from AI-powered diagnostic tools that allow for remote consultations and disease screening. AI-based telemedicine platforms and mobile apps are making healthcare more accessible in underserved areas.
- **Instantaneous Data Evaluation:** AI is utilized to process live patient data collected from wearable devices and health monitors, allowing for the early identification of conditions such as heart disease, diabetes, and high blood pressure. This enables healthcare professionals to take timely action and deliver preventive care, thereby easing pressure on healthcare systems.

(4) AI in Bioprocessing and Manufacturing:

- **Optimized Biomanufacturing:** AI is revolutionizing biomanufacturing by improving the management of production settings like bioreactors. Predictive machine learning models help optimize conditions to achieve higher yield and quality in producing biopharmaceuticals, vaccines, and various biotech products.

- **Cost Reduction and Efficiency:** In biotech manufacturing, AI contributes to lowering operational expenses by automating repetitive tasks, enhancing process efficiency, and minimizing waste. In India, it supports companies in expanding production while maintaining uniform product quality.
- **Quality Assurance and Forecast-Based Maintenance:** AI-powered systems are being employed in quality control to detect anomalies in production and packaging. Additionally, predictive maintenance powered by AI helps in minimizing equipment downtime, ensuring smoother manufacturing operations.

9.2 ABCD Evaluation of AI Integration in the Indian Biotechnology Sector from the Perspective of Stakeholders:

The research process is defined in various ways, commonly as creating new knowledge or reinterpreting existing knowledge through analysis. The ABCD analysis is one such flexible framework, usable in both qualitative and quantitative research. It helps evaluate organizational concepts, technologies, and strategies by examining factors like business, customer, technological, and societal influences [79-88]. The framework identifies advantages, benefits, limitations, and drawbacks, making it useful in assessing biotechnological advances like biopharmaceuticals and GMOs, especially in addressing societal and environmental challenges.

(i) Stakeholder Perspectives on the Benefits of AI Implementation in India's Biotechnology Sector:

Under the ABCD (Advantages, Benefits, Constraints, and Disadvantages) analysis framework, several key advantages of AI adoption in the Indian biotechnology sector are highlighted from the perspectives of various stakeholders (Table 8).

Table 8: Advantages of AI adoption in the Indian biotechnology industry from various stakeholders' perspectives

S. No	Key Advantage	Description
1	**Accelerated Drug Discovery & Development (Pharmaceutical Perspective)**	(i) AI-driven simulations and predictive modelling reduce drug discovery time and costs. (ii) Machine learning algorithms analyse biomedical data for faster target identification.
2	**Better Precision in Personalized Medicine (Healthcare Perspective)**	(i) AI analyses genetic data to tailor treatments based on individual patient profiles. (ii) AI models improve disease diagnosis and treatment planning accuracy.
3	**Cost Reduction in Research & Development (Biotech Companies' Perspective)**	(i) AI-driven automation optimizes laboratory experiments, reducing manual effort. (ii) Predictive analytics minimize failed trials, saving research costs.
4	**Data-Driven Crop Biotechnology (Agricultural Perspective)**	(i) AI optimizes genetically modified crops for higher yields and disease resistance. (ii) Machine learning enhances precision agriculture and soil health monitoring.
5	**Enhanced Biomanufacturing Processes (Industrial Perspective)**	(i) AI optimizes bioprocessing, improving yield and efficiency in vaccine and enzyme production. ii) Real-time AI monitoring ensures quality control in biomanufacturing.
6	**Faster Disease Surveillance & Outbreak Prediction (Public Health Perspective)**	(i) AI models analyse epidemiological data to predict and control disease outbreaks. (ii) Early detection of pandemic risks enables proactive healthcare responses.
7	**Genomics & Proteomics Advancements (Scientific**	(i) AI accelerates sequencing analysis, uncovering new biomarkers and gene functions.

	Research Perspective)	(ii) Deep learning enhances protein structure prediction for drug development.
8	**High Efficiency in Clinical Trials. (Regulatory & Ethical Perspective)**	(i) AI helps identify suitable trial participants, reducing bias and improving results. (ii) Predictive analytics streamline regulatory approval processes.
9	**Intelligent Bioinformatics Solutions (Technology Perspective)**	(i) AI-powered tools process complex biological data for genome annotation and protein modeling. (ii) AI assists in understanding biological pathways for novel therapies.
10	**Job Creation & Upskilling Opportunities (Economic & Workforce Perspective)**	(i) AI adoption in biotech increases demand for skilled professionals in data science and bioinformatics. (ii) Continuous learning programs help create a workforce adept at AI-driven biotech innovations

Integrating AI into the Indian biotechnology sector brings multiple benefits, such as improved medication discovery, reduced costs, tailored treatments, and accelerated clinical trials. AI enhances decision-making, boosts efficiency, and drives innovation in diagnostics, playing a vital role in the industry's growth and progress.

(ii) Stakeholders' Perspectives on the Benefits of AI Adoption in the Indian Biotechnology Industry:

Using the ABCD (Advantages, Benefits, Constraints, and Disadvantages) analysis framework, ten major benefits of AI adoption in the Indian biotechnology sector are presented, organized according to the viewpoints of various stakeholders (Table 9).

Table 9: Benefits of AI adoption in Indian Biotechnology Industry from Stakeholder's perspectives

S. No.	Key Benefits	Description
1	**Enhanced Drug Discovery &Development (Pharmaceutical Perspective)**	(i) AI accelerates drug discovery by analysing vast biological datasets. (ii)Reduces research time and costs by identifying Potential drug candidates efficiently.
2	**Precision Medicine & Personalized Healthcare (Healthcare Perspective)**	(i) AI tailors treatments based on genetic and clinical data. (ii) Improves patient outcomes with customize d therapies.
3	**Efficient Clinical Trials & Data Analysis (Medical Research Perspective)**	(i) AI helps identify suitable candidates for clinical trials. (ii) Predicts treatment responses, reducing trial duration and costs.
4	**Advanced Genomics Research (Scientific Research Perspective)**	(i) AI-driven bioinformatics enhances gene sequencing and analysis. (ii) Facilitates breakthroughs in genetic engineering and disease resistance.
5	**Improved Disease Diagnosis & Prediction (Healthcare & Patient Perspective)**	(i) AI-based diagnostics detect diseases early for timely intervention. (ii) Enhances medical imaging analysis, leading to accurate diagnosis.
6	**Enhanced Agricultural Biotechnology (Agriculture & Farming Perspective)**	(i) AI optimizes crop genetics and pest resistance. (ii)Predicts crop yield and ensures food security.
7	**Cost Reduction in Biotech R&D (Economic & Industry Perspective)**	(i) AI automates research processes, reducing manual efforts. (ii)Cuts operational costs and accelerates innovation.

8	**AI-Powered Regulatory Compliance (Regulatory & Ethical Perspective)**	(i) AI helps biotech firms comply with safety and ethical regulations (ii) Reduces risks of regulatory violations and enhances transparency.
9	**Faster Biopharma Manufacturing (Industry & Production Perspective)**	(i) AI optimizes production processes for higher yields. (ii) Ensures consistent quality and reduces manufacturing defects.
10	**Sustainable Environmental Biotechnology (Environmental perspective)**	(i) AI aids in bio-remediation and waste management. (ii) Supports biofuel production for sustainable energy solutions.

AI adoption in India's biotechnology industry is driving innovation, efficiency, and sustainability in healthcare, pharmaceuticals, and agriculture. It speeds up drug discovery, enhances precision medicine and diagnostics, and optimizes clinical trials while cutting costs. AI also improves regulatory compliance, biopharma production, and environmental sustainability. With responsible use, it can transform biotechnology, advancing healthcare, economic growth, and global competitiveness.

(iii) Stakeholders' Perspectives on the Challenges of AI Adoption in the Indian Biotechnology Industry:

Within the ABCD (Advantages, Benefits, Constraints, and Disadvantages) analysis framework, ten major constraints of AI adoption in the Indian biotechnology sector are outlined, categorized based on the perspectives of various stakeholders (Table 10).

Table 10: Constraints of AI adoption in the Indian biotechnology industry from various stakeholders' perspectives

S. No.	Key Constraints	Description
1	**High Implementation Costs (Economic & Industry Perspective)**	(i) AI adoption requires significant investment in infrastructure, software, and skilled workforce. (ii) Small and mid-sized biotech firms may struggle with affordability.
2	**Data Privacy & Security Concerns (Regulatory & Ethical Perspective)**	(i) Handling sensitive genetic and medical data raises privacy risks. (ii) Cybersecurity threats can compromise Confidential research.
3	**Lack of Skilled Workforce (Workforce & Training Perspective)**	(i) The biotechnology industry lacks professionals trained in AI, bioinformatics, and data science. (ii) Upskilling employees requires time and investment
4	**Regulatory & Compliance Challenges (Government & Policy Perspective)**	(i) AI application s in biotechnology must comply with strict ethical and legal guidelines. (ii) Rapid AI advancement often outpace existing regulations.
5	**Data Availability & Quality Issues (Scientific Research Perspective)**	(i) AI models require large, high-quality datasets for accuracy. (ii) Limited access to diverse and standardized datasets hampers AI efficiency.
6	**Ethical Concerns in AI-Driven Research (Public & Ethical Perspective)**	(i) AI in genetic modifications and drug discovery raises bioethical issues. (ii) Potential misuse of AI for unethical experimentation is a major concern.
7	**Integration Challenges with Existing Systems (Technology & Infrastructure Perspective)**	(i) Many biotech firms use legacy systems that are incompatible with AI. (ii) Transitioning to AI-driven solutions requires extensive restructuring.

8	**Risk of Bias & Inaccuracy in AI Models (Healthcare & Patient Perspective)**	(i) AI algorithms can produce biased results due to incomplete or skewed training data. (ii) Inaccurate AI predictions in diagnostic s and drug development can have serious consequences.
9	**Limited AI Awareness & Adoption (Industry & Market Perspective)**	(i) Many biotech firms are unaware of AI's potential benefits. (ii) Hesitation to invest in AI due to uncertainty about ROI slows adoption.
10	**Dependence on Foreign AI Technologies (National & Economic Perspective)**	(i) Indian biotech firms rely heavily on imported AI solutions. (ii) Lack of indigenous AI development limits self-sufficiency and innovation.

AI adoption in the Indian biotechnology industry faces multiple constraints, including high costs, regulatory hurdles, data privacy concerns, and a lack of skilled professionals. While AI offers significant potential for innovation, overcoming these challenges requires policy reforms, investment in AI infrastructure, cybersecurity measures, and workforce development. Addressing these issues will enable the biotechnology sector to harness AI's full potential for research, healthcare, and industrial applications.

(iv) Stakeholders' Views on the Drawbacks of AI Adoption in the Indian Biotechnology Industry: Using the ABCD (Advantages, Benefits, Constraints, and Disadvantages) analysis framework, several significant disadvantages of AI adoption in the Indian biotechnology sector are identified, organized according to the viewpoints of various stakeholders (Table 11).

Table 11: Disadvantage of AI adoption in the Indian biotechnology industry from various stakeholders' perspectives

S. No.	Key Disadvantage	Description
1	**High Implementation Costs (Economic & Industry Perspective)**	(i) AI models require high-quality well-struct ured datasets for accurate results. (ii) Poor or biased data can lead to incorrect predictions and flawed research outcomes.
2	**Job Displacement & Workforce Challenges (Human Resource Perspective)**	(i) AI automation may replace traditional biotech jobs, leading to workforce displacement. (ii) Skilled professionals need reskilling to work alongside AI-driven systems.
3	**Ethical Concerns in AI-Driven Research (Regulatory & Society Perspective)**	(i) AI in genetic engineering and drug discovery raises ethical concerns about data privacy and human intervention. (ii) The lack of transparency in AI decision-making complicates ethical compliance.
4	**Risk of Algorithm Bias & Unreliable Predictions (Customer & Society Perspective)**	(i) AI models can exhibit biases in clinical trials and genetic research. (ii) Unreliable AI-generate d predictions may result in ineffective or unsafe treatments.
5	**Security & Cyber Threats (Security & Risk Perspective)**	(i) AI systems in biotech are vulnerable to cyberattacks, exposing sensitive patient and research data. (ii) Weak security measures may lead to data breaches and misuse.
6	**Regulatory Compliance Barriers (Government & Regulatory Perspective)**	(i)Stringent regulations for AI application s in biotechnology slow down research and development. (ii) AI-driven healthcare solutions must comply with strict ethical and legal guidelines
7	**High Implementation & Maintenance Costs (Investor & Business Perspective)**	(i) AI infrastructure, software, and skilled personnel require significant investment (ii) Small biotech firms may struggle with the financial burden of AI adoption.

8	**Lack of Human Oversight in Critical Decision-Making (Operation al Perspective)**	(i) Over-reliance on AI in drug research and diagnostic s may reduce human expertise. (ii) AI errors without human intervention can lead to serious consequences in medical treatments
9	**Limited Adoption in Rural & Small-Scale Biotech Research (Financial Inclusion Perspective)**	(i) AI adoption remains low in rural biotech research centres due to infrastructure and funding challenges. (ii) Low digital literacy hinders AI-based innovations in small-scale biotech firms.
10	**Uncertain ROI & Long-Term Viability (Investor & Business Perspective)**	(i) The return on investment (ROI) for AI in biotechnology remains uncertain. (ii)AI-driven innovation s may not yield immediate financial benefits, discouraging large-scale adoption.

While AI holds the promise to transform the Indian biotechnology sector, its implementation also presents notable challenges. Challenges such as high implementation costs, job displacement, ethical concerns, algorithm biases, cybersecurity risks, and regulatory barriers hinder seamless integration. Additionally, the uncertainty of ROI and limited adoption in rural areas further slowdown progress.

10. IMPACT OF AI ON BIOTECHNOLOGY OPERATIONS:

10.1 General Impact of AI in biotechnology:

(1) AI Adoption and Key Drivers in Biotechnology:
The integration of AI with biotechnology creates new opportunities to address global challenges and support Sustainable Development Goals, such as food security, health, clean water and energy, climate action, and ecosystem protection. AI influences life sciences through machine learning, Big Data analytics, data mining, biomedical ontologies, decision-making, NLP, and explainable AI (XAI). This paper reviews key research challenges and gaps in these areas, offering guidance for researchers exploring these topics (Mehta et al. (2024). [89]).
(2) Benefits of AI in Biotechnology:
AI offers major benefits in biotechnology, especially in drug discovery, where it identifies promising candidates, predicts molecular interactions, and improves clinical trial design. Companies like DeepMind and Benevolent AI use AI to cut costs and time in drug development. In personalized medicine, AI analyses genetic and clinical data to create tailored treatments. It also supports genomic research and gene editing by detecting disease-related mutations, advancing genetic understanding and treatment options (Kumar et al. (2025). [90]).
(3) Risks Associated with AI in the Biotechnology Sector:
Although AI offers many advantages in biotechnology, it also comes with certain risks. A key issue is data privacy, since applying AI in genomic and medical research brings ethical challenges regarding the protection of sensitive patient data. Additionally, AI models that are trained on biased data may lead to inaccurate predictions, which can impact drug development and medical diagnostics.
Regulatory and ethical concerns also emerge, as AI-powered biotechnologies need rigorous monitoring to guarantee safety and adherence to applicable regulations. Furthermore, there are cybersecurity risks, as AI systems in biotech can be vulnerable to cyber-attacks, putting sensitive data and research integrity at risk (Gomes et al. (2024). [91]).

10.2 Specific AI Applications in Biotechnology:

(1) Artificial Intelligence in Pharmaceutical Research and Development
AI is transforming drug discovery and development by speeding up the identification of promising drug candidates. By leveraging machine learning techniques, AI can process large amounts of data such as molecular structures, genetic profiles, and clinical trial results to forecast how various compounds will interact with specific biological targets.
Moreover, AI is reshaping the clinical trial phase by making it more efficient and cost-effective. It achieves this by predicting patient responses, selecting appropriate trial participants, and enhancing recruitment methods, thereby streamlining the overall trial process (Ali et al. (2024). [92]).

(2) AI in Genomic Research and Gene Editing:
AI is transforming genomic research by rapidly analysing complex genetic data, identifying disease-linked patterns and mutations, and predicting the impact of genetic changes. This supports the development of targeted treatments. In gene editing, particularly with CRISPR, AI boosts precision and effectiveness by processing experimental data to refine techniques. AI also plays a key role in personalized medicine by helping design therapies tailored to individual genetic profiles, improving treatment accuracy and outcomes (Phillip (2026). [93]).

(3) AI in Personalized Medicine:
AI is revolutionizing personalized medicine by creating treatment plans tailored to each patient's genetics, medical history, and lifestyle. It analyses data like genetic sequences, medical images, and health records to uncover patterns unseen by clinicians. This enables more precise, effective therapies. By combining genetic and clinical data, AI helps predict treatment responses, leading to more customized and successful care strategies.
AI plays a key role in personalized medicine by enabling real-time patient monitoring and adaptive treatment plans. It analyses continuous health data to detect changes and suggest timely adjustments. In oncology, companies like Tempus use AI to design personalized cancer therapies by examining tumor genetics and patient health data. This approach improves outcomes, reduces trial-and-error, and minimizes side effects by targeting treatments to each patient's specific needs (Sharma & Singh (2026). [94]).

(4) The Role of Artificial Intelligence in Diagnostic Imaging:
Artificial intelligence is transforming diagnostic imaging by increasing both the speed and accuracy of identifying medical conditions. Using advanced computer vision algorithms, AI systems can examine medical images such as X-rays, MRIs, and CT scans with high precision. These technologies are trained to recognize subtle patterns that might be missed by the human eye, enabling early detection of diseases such as cancer, cardiovascular issues, and neurological disorders. In some cases, AI can identify irregularities before physical symptoms emerge, supporting earlier interventions and improving patient prognosis. In some cases, AI has been shown to match or even surpass the diagnostic accuracy of expert clinicians, providing an additional layer of confidence in diagnoses.
AI's capability to rapidly analyse vast amounts of imaging data in real time greatly enhances the speed of diagnosis, which is especially crucial in emergency care where swift decisions are vital. For example, some AI technologies can now detect over 50 eye conditions with a level of accuracy comparable to that of seasoned ophthalmologists, allowing for faster triage of urgent cases. By handling repetitive tasks in diagnostic imaging, AI eases the workload of medical staff and improves overall workflow, allowing clinicians to concentrate more on direct patient care. As AI technology evolves, its impact on diagnostic imaging is expected to grow, delivering even more accurate and timely assessments across a wide range of medical specialties (Takeda (2025). [95]).

10.3 Impact on Biotechnology industry Customer:

(1) Enhanced Product Development and Innovation:
AI is transforming biotechnology by streamlining drug discovery and development. It processes large datasets like genetic info, molecular structures, and trial results to quickly identify promising drug candidates. This speeds up the development process and reduces dependence on trial-and-error methods. As a result, biotech companies can more efficiently deliver innovative treatments for conditions like cancer, rare diseases, and genetic disorders.
For customers, this means faster access to cutting-edge treatments, particularly in areas where new drugs or therapies have been historically difficult to develop. AI-powered innovations in biotechnology are paving the way for more personalized treatments, tailored to an individual's genetic makeup. This approach not only increases the effectiveness of therapies but also helps minimize side effects, resulting in more individualized and precise healthcare solutions. Furthermore, by streamlining research and development processes, AI helps biotech companies reduce costs and focus their efforts on the most promising projects. As a result, patients gain access to a wider variety of innovative and cost-effective treatment options (DSVNM et al (2024). [96]).

(2) Increased Precision in Diagnostics and Personalized Medicine:
AI is revolutionizing biotechnology services by improving the precision of diagnostics and enabling the rise of personalized medicine. Diagnostic tools powered by AI, utilizing machine learning and deep learning techniques, are capable of examining medical images, genetic information, and biomarkers to detect diseases or assess health risks early on. Additionally, AI supports the creation of companion diagnostics tests designed to pinpoint patients who are most likely to respond positively to specific medications thereby improving the precision and success of treatment plans.
For biotechnology customers, this shift toward personalized medicine represents a more tailored, data-driven approach to healthcare. Customers will experience treatments and interventions that are more suited to their unique biological makeup, leading to higher efficacy and fewer adverse reactions. This approach not only improves the patient experience but also enables individuals to actively manage their health, confident that their care is tailored through sophisticated AI-driven insights (Spencer (2025). [97]).

(3) Streamlined Biotechnology Services and Operational Efficiency:
AI technology is streamlining biotechnology operations by automating many labour-intensive tasks involved in research, manufacturing, and supply chain management. Within the laboratory setting, AI can automate the examination of experimental data, rapidly uncovering patterns and irregularities that might take researchers much longer to notice. Additionally, AI helps streamline laboratory operations, including sample processing and data gathering, which accelerates the overall pace of research. In manufacturing, AI is used to monitor production lines in real-time, ensuring quality control and optimizing the production of biologics and other biotechnology products.
For customers, the impact of these operational efficiencies translates into faster delivery of products, higher-quality therapies, and more consistent results. By automating repetitive tasks, biotechnology companies can reduce human error, ensuring that customers receive products with higher precision and reliability. The improved manufacturing processes also reduce the cost of production, making treatments more affordable and accessible. These operational improvements enhance the overall customer experience by ensuring timely delivery, reduced costs, and more reliable outcomes in the biotechnology sector (Artico et al. (2022). [98]).

(4) Impact on Biotechnology Employment:
AI's integration into biotechnology operations is transforming the workforce. Although automation can decrease the demand for some manual and repetitive jobs, it is also generating new career prospects in areas such as data science, machine learning, and the management of AI systems. This shift encourages a focus on upskilling and reskilling the workforce, enabling biotechnology professionals to engage with cutting-edge technologies and contribute to innovation in the sector.
For customers, the effect on employment is positive, as the growing need for specialized positions in biotechnology fosters a more skilled workforce that can propel scientific progress. The rise of AI specialists, data scientists, and bioinformaticians within the industry guarantees ongoing innovation, resulting in the creation of more advanced and effective biotechnology solutions and services. This growth in highly skilled roles benefits customers by enhancing the overall quality of research and products offered, contributing to a healthier, more innovative biotechnology landscape.

10.4 Impact on the Biotechnology Industry:
(1) Rapid Advancement in Drug Discovery and Development:
AI is revolutionizing biotechnology by accelerating the drug discovery process. Unlike traditional methods, AI quickly analyses genetic data, molecular structures, and clinical trial results with high precision. Using machine learning, it predicts the most promising drug candidates and simulates biological interactions, helping scientists discover new compounds and understand how they work. This streamlines and optimizes the entire development process.
This faster approach helps biotechnology firms cut down on the time and expenses involved in drug development, enabling them to introduce new treatments to the market more quickly. For the industry, this means a competitive edge, as companies can develop cutting-edge drugs more efficiently, particularly in areas like oncology, gene therapy, and personalized medicine. Ultimately, AI-driven

innovation in drug discovery is poised to lead to breakthroughs in previously untreatable or hard-to-target diseases, significantly advancing the biotechnology industry (Nagamarpalli (2021). [99]).

(2) Enhanced Precision Medicine and Personalized Healthcare:
AI is crucial in driving progress in personalized medicine by helping biotechnology companies create therapies customized to an individual's genetic makeup. By analysing extensive genomic data and recognizing disease-related patterns, AI enables the development of more accurate and effective treatments. This is particularly prominent in areas such as cancer care, where precision medicine is increasingly the norm, providing targeted treatments that improve results and reduce adverse effects.
Personalized medicine opens up a new horizon for product innovation in the biotechnology sector, with AI serving as a vital tool in developing therapies that are both more effective and carry a lower risk of side effects. Biotechnology companies that adopt AI in this area will have access to a growing market of patients who are increasingly seeking treatments tailored to their genetic profiles. The shift toward precision medicine is transforming the industry, leading to more individualized care and opening up new revenue streams for biotech companies focused on genetics, diagnostics, and custom therapeutic solutions (Oyeniran et al. (2025). [100]).

(3) Improved Operational Efficiency and Cost Reduction:
AI is enhancing biotech operations by automating tasks like data collection, analysis, and experiment monitoring. In R&D labs, it processes large datasets, identifies patterns, and aids experiment design, reducing manual work and saving time. AI also streamlines lab workflows and manufacturing, cutting costs and boosting efficiency. By predicting issues like bottlenecks or quality problems, it helps prevent delays and ensures faster, more cost-effective drug production.
By streamlining operations, AI allows biotechnology companies to redirect their resources toward innovation and more high-value activities, such as advancing R&D or developing new therapeutic solutions. For the industry, this means a more agile and responsive organization, able to meet market demands faster and more efficiently. Ultimately, the reduction in operational costs and the improvement in efficiency help biotechnology companies remain competitive in an increasingly demanding and cost-conscious market, benefiting both the companies themselves and their customers (Alaa et al. (2025). [101]).

10.5 Regulatory and Ethical Considerations of Artificial Intelligence in Biotechnology:

(1) Privacy and Security in Data Management:
A major ethical concern in AI-driven biotechnology is safeguarding sensitive patient data. Biotech companies, especially in genomics and personalized medicine, depend on large datasets to train AI models, making data privacy critical. Regulations like GDPR and HIPAA help protect this information. However, the complexity of AI and the global nature of biotech demand a careful balance between using data for innovation and protecting individual privacy. Firms must implement strong security measures to prevent data breaches and ensure ethical, lawful use of personal health information (Izankar et al. (2024). [102]).

(2) Transparency and Explainability:
AI technologies, especially in areas like drug discovery, diagnostics, and personalized treatment planning, frequently operate as "black boxes," where the reasoning behind their decisions is not always clear. This opacity poses difficulties in making sure that AI systems function in a manner that is both understandable and justifiable to healthcare professionals and patients alike. The regulatory challenge lies in guaranteeing that AI models are not only efficient but also sufficiently transparent to comply with ethical and legal requirements.
For biotechnology companies, this means developing AI tools that provide explanations for their decisions, especially in high-stakes environments like clinical diagnostics and drug development. Ethical concerns arise when patients or healthcare professionals cannot understand why a certain treatment is recommended or a diagnosis is made, undermining trust in the system. Regulatory authorities will need to implement guidelines that require AI systems to have interpretability, ensuring accountability and trust in AI-driven biotech operations (Popović et al. (2024). [103]).

(3) Algorithmic Bias and Fairness:
The effectiveness of AI systems depends heavily on the quality of the data used for training, and if this data contains biases, the models produced may result in unfair or unequal outcomes. In biotechnology, this bias could manifest in drug development, diagnostic tools, or personalized treatments that disproportionately benefit certain demographic groups while neglecting others. For example, an AI model developed primarily using data from a single ethnic group may struggle to deliver accurate results for patients of different ethnic backgrounds, potentially contributing to healthcare inequalities. Ethical concerns arise regarding the potential harm caused by these biases, which could exacerbate existing inequalities in healthcare access and outcomes.
To overcome these issues, biotechnology firms must train their AI systems on diverse datasets that encompass a wide range of populations to prevent biased outcomes. Additionally, regulatory bodies may need to establish guidelines promoting fairness and equity in AI models to guarantee that advancements in biotechnology benefit all patients, irrespective of their demographic or background (Holzinger et al. (2023). [104]).

(4) Impact on Human Employment and Skill Requirements:
AI's integration into biotechnology operations is likely to change the workforce dynamics in the industry, raising both regulatory and ethical questions regarding employment. As AI takes over repetitive or data-intensive tasks, such as lab work, data analysis, and patient monitoring, some jobs may be displaced or transformed. At the same time, this transition opens up opportunities for new positions demanding expertise in AI development, data science, and bioinformatics. Ethical issues emerge regarding possible job displacement and the importance of implementing reskilling and upskilling initiatives to support workers in adapting to these new roles.
Biotechnology companies will need to ensure they are supporting their employees by investing in training and education, and regulatory bodies may need to implement policies to protect workers from being left behind in this technological shift. Additionally, the ethical concern of AI replacing human workers in roles that require empathy, such as patient-facing positions, must be considered. AI should complement human expertise, not replace the essential human element in biotechnology services.

10.6 Recommendations for Ethical and Regulatory AI Adoption:

(1) Develop Clear Regulatory Guidelines: Regulatory authorities need to establish clear and flexible guidelines to manage the approval and application of AI in the biotechnology sector. These guidelines should focus on ensuring that AI tools meet safety, efficacy, and ethical standards, while also remaining flexible to accommodate new AI advancements in biotechnology (Sharma & Singh (2025). [105]).
(2) Protecting Data Privacy and Security: Since AI depends extensively on patient and genetic information, it is essential to enforce stringent data privacy protocols. Biotechnology firms must adhere to data protection regulations such as GDPR and HIPAA, guaranteeing that all patient data is managed responsibly and securely to safeguard individual privacy (Laith et al. (2025). [106]).
(3) Promote Transparency in AI Systems: AI tools used in biotechnology should be transparent and explainable. It's essential for AI models, especially those involved in drug development or diagnostics, to provide understandable explanations for their decisions to build trust with healthcare professionals and patients.
(4) Prevent Algorithmic Bias: To prevent biased results that may cause unfair treatment, AI systems need to be developed using varied and representative datasets. Ethical guidelines should focus on ensuring AI models are fair and inclusive, offering equal treatment and accuracy for all demographic groups.
(5) Encourage Continuous Ethical Training: Biotechnology companies should prioritize ongoing ethical training for employees involved in AI development and implementation. This ensures that staff are aware of the ethical implications of AI and understand how to use AI responsibly in biotechnology applications.

11. PESTEL ANALYSIS :

PESTEL analysis helps assess external factors influencing AI adoption in biotechnology by examining Political, Economic, Social, Technological, and Legal aspects. Politically, it involves policies and R&D funding. Economically, it looks at implementation costs, investment, and benefits like improved drug development. Legally, it covers data privacy, IP rights, and ethics. This framework helps biotech firms navigate challenges and make informed decisions.

11.1 Political Factors Affecting the Adoption of AI in India’s Biotechnology Sector:

Below are ten political environmental factors impacting the adoption of AI in India’s biotechnology sector, analysed through the PESTEL framework [107-108]:

(1) Administrative Policies and Initiatives: The Indian government's policies on promoting biotechnology and AI innovation, such as the National Biotechnology Development Strategy and initiatives like Atmanirbhar *Bharat*, play a critical role in supporting AI adoption within the sector.

(2) Regulatory Framework for Biotechnology: The presence or absence of clear and updated regulations for AI and biotechnology, including drug approvals, clinical trials, and diagnostics, influences how companies integrate AI into their operations.

(3) Government Funding for Research: Political decisions regarding the allocation of funding for AI research and biotechnology innovation, including government grants and incentives, encourage growth and adoption of AI technologies in biotechnology.

(4) Data Privacy and Protection Laws: Policies related to data privacy, like the Personal Data Protection Bill (PDPB), impact how biotech companies manage patient and genetic data when adopting AI technologies.

(5) Intellectual Property Rights (IPR) Policies: The Indian government's approach to intellectual property laws, including patents related to AI algorithms and biotechnological products, affects the commercialization of AI innovations in the biotech sector.

(6) Collaboration with International Bodies: Political relations and agreements between India and international organizations or governments can influence access to AI research, development collaboration, and biotechnology partnerships that help accelerate AI adoption.

(7) Tax Incentives and Subsidies: Government tax breaks, subsidies, or incentives for companies investing in AI and biotechnology innovations can make the adoption of AI more affordable and attractive to businesses.

(8) Political Stability and Policy Continuity: Political stability in India ensures the continuity of AI-related policies, giving companies confidence to invest in long-term AI projects within the biotechnology industry.

(9) Public Health Initiatives and AI Adoption: State-led programs aimed at enhancing public health, including initiatives like Ayushman Bharat and various healthcare reforms, have the potential to incorporate AI into biotechnology applications such as diagnostics, disease management, and customized treatment strategies.

(10) Geopolitical Tensions and Import/Export Restrictions: Political tensions or trade restrictions on key materials, data, or AI technologies can impact the flow of AI tools or expertise into India, affecting the pace of AI integration in biotechnology.

The political factors influencing AI adoption in India's biotechnology sector play a pivotal role in shaping the industry's growth and innovation. Government policies, regulatory frameworks, funding initiatives, and data privacy laws directly impact the pace at which AI technologies can be integrated into biotechnology operations.

11.2 Economic Factors Impacting the Adoption of AI in India’s Biotechnology Sector:

Below are ten economic environmental factors affecting the adoption of AI in India’s biotechnology industry, examined through the PESTEL analysis framework [109]:

(1) High Initial Investment Costs: Implementing AI technologies requires substantial investment in software, hardware, cloud infrastructure, and skilled professionals, making adoption challenging for many biotechnology firms, especially startups and SMEs.

(2) Availability of Funding and Venture Capital: Access to government grants, venture capital, and private equity encourages biotechnology companies to invest in AI-driven research, drug discovery, and healthcare innovations.

(3) Research and Development (R&D) Expenditure: Organizations with higher R&D budgets are better positioned to integrate AI into genomics, bioinformatics, precision medicine, and biotechnology research.

(4) Cost Reduction and Operational Efficiency: AI helps automate laboratory processes, optimize clinical trials, and improve manufacturing efficiency, significantly reducing operational costs and increasing productivity.
(5) Government Financial Incentives: Subsidies, tax benefits, and initiatives such as Digital India, Startup India, and biotechnology funding schemes encourage AI adoption across the sector.
(6) Availability of Affordable Digital Infrastructure: The declining cost of cloud computing, high-performance computing (HPC), and data storage makes AI solutions more accessible to biotechnology organizations.
(7) Market Competition and Global Competitiveness: Intense domestic and international competition motivates biotechnology firms to adopt AI for faster innovation, improved product quality, and competitive advantage.
(8) Return on Investment (ROI) Expectations: Companies are more likely to invest in AI when they anticipate measurable financial benefits, such as faster drug development, improved diagnostics, and increased profitability.
(9) Skilled Workforce and Labor Costs: The availability of AI professionals, data scientists, bioinformaticians, and machine learning experts, along with their salary levels, significantly influences AI implementation costs.
(10) Growth of India's Biotechnology Market: The expanding biotechnology industry, rising healthcare expenditure, increasing pharmaceutical demand, and growing investment in life sciences create strong economic incentives for AI adoption and innovation.
In conclusion, economic factors are crucial in determining the pace at which AI is adopted in India’s biological industry. Access to funding, cost benefits, market demand, and the competitive landscape all influence companies' decisions to invest in AI technologies

11.3 Social Factors Impacting AI Adoption in India’s Biotechnology Sector:

Ten Social Environmental Factors Affecting AI Adoption in India’s Biotechnology Industry According to the PESTEL Analysis Framework [110]:
(1) Public Perception of AI: Public trust in AI technologies, especially in healthcare and biotechnology, can influence adoption. If the public perceives AI as a reliable and safe tool, there is a higher likelihood of acceptance.
(2) Awareness and Education: The level of awareness about AI’s capabilities and potential in biotechnology, including its applications in drug development, diagnostics, and personalized medicine, impacts how readily it is adopted by both professionals and the public.
(3) Ethical Concerns: Public worries regarding AI in biotechnology, including concerns over data privacy and the possibility of AI replacing healthcare jobs, could influence societal acceptance and the rate of AI adoption.
(4) Cultural Acceptance: Cultural attitudes towards new technologies in India, especially in healthcare, can affect the speed of AI adoption. Some communities may be more hesitant to accept AI-driven treatments or diagnostics.
(5) Access to Healthcare: AI can enhance healthcare availability in underserved regions by offering cost-effective diagnostic solutions and tailored treatment options. This could address disparities in healthcare and boost AI adoption in rural areas.
(6) Job Displacement Concerns: Social concerns regarding AI-driven job displacement in the biotechnology and healthcare sectors may affect workforce morale and the overall acceptance of AI within the industry.
(7) Social Inequality and Healthcare Access: The implementation of AI must consider its impact on reducing or exacerbating healthcare inequalities. If AI technologies are accessible only to affluent populations, they may widen existing social disparities in healthcare.
(8) Collaborations Between Academia, Industry, and Society: The level of collaboration between academic institutions, biotech companies, and society influences how AI is integrated. Strong partnerships can foster innovation and support the social acceptance of AI in biotechnology.
(9) Consumer Trust in AI for Healthcare: The willingness of patients and healthcare providers to trust AI in diagnosis and treatment can significantly impact the adoption of AI-powered biotechnology products and services.

(10) Impact on Traditional Healthcare Practices: The shift from traditional methods to AI-based solutions can create resistance among healthcare professionals and patients accustomed to older systems, affecting the rate of AI adoption in biotechnology.
In summary, social elements greatly impact the acceptance of AI within India's biotechnology sector. Factors such as public opinion, cultural beliefs, ethical considerations, and AI's ability to reduce healthcare disparities all affect its reception.

11.4 Technological Elements Affecting AI Integration in India's Biotechnology Sector:

Below are ten technological environmental factors impacting the adoption of AI in India's biotechnology industry, evaluated through the PESTEL analysis framework [111]:
(1) Progress in Machine Learning Techniques: Ongoing advancements in machine learning and deep learning techniques boost AI's capacity to handle vast datasets, forecast drug interactions, and interpret genomic information, driving faster progress in biotechnology.
(2) Advanced Data Analytics: Access to and examination of large-scale data, such as genetic information, clinical trial results, and patient histories, enables AI systems to generate valuable insights, supporting more accurate drug development, diagnostics, and tailored treatments.
(3) Cloud Computing: Cloud-based services allow biotechnology firms to securely store large volumes of data and utilize AI tools for processing without investing in costly on-site infrastructure, lowering expenses and enhancing scalability.
(4) High-Performance Computing (HPC): The ability to conduct complex computations and simulations quickly is essential in biotechnology for drug design, protein folding, and genetic research. AI adoption in HPC enhances productivity and efficiency in these areas.
(5) Integration of AI with Laboratory Automation: AI-driven automation in laboratories, such as robotic systems for drug discovery and DNA sequencing, speeds up research while improving accuracy and reducing human error in biotech experiments.
(6) Advanced Biotechnology Tools: The development of AI-powered tools, like CRISPR-based gene editing systems and diagnostic imaging, enhances precision in research and clinical practices, allowing for more effective and accurate treatments.
(7) Bioinformatics Platforms: Incorporating AI into bioinformatics applications helps interpret intricate biological information, like genetic sequences and protein configurations, thereby accelerating research and innovation in the biotechnology field.
(8) Connected Devices and Health Monitoring Technologies: Integrating AI with connected health devices and wearable technology in biotechnology enables real-time monitoring of patient conditions, supplying valuable data for customized treatment approaches and supporting advancements in drug research.
(9) AI-Driven Medication Repositioning: AI algorithms are capable of examining current pharmaceutical compounds to uncover new potential applications, greatly cutting down both the time and expense involved in developing treatments by finding new uses for existing formulations.
(10) Genomic Sequencing Technologies: AI's integration with next-generation sequencing technologies enables faster, more accurate analysis of genomes, providing vital data for understanding genetic disorders and tailoring personalized therapies.
To sum up, technological advancements are key drivers of AI adoption in India's biotechnology sector. Progress in intelligent algorithms, advanced data analysis, and cloud-based solutions is helping biotech firms speed up therapeutic discovery, improve diagnostic precision, and deliver better healthcare results.

11.5 Legal Factors Affecting AI Implementation in India's Biotechnology Sector:

Below are ten legal factors impacting the adoption of AI in India's biotechnology industry, evaluated through the PESTEL analysis framework [112]:
(1) Data Protection and Privacy Laws: Compliance with India's data protection regulations, particularly for sensitive health and genomic data, is essential for AI adoption in biotechnology.
(2) Intellectual Property Rights (IPR): Strong patent, copyright, and trade secret laws protect AI algorithms, biotechnology innovations, and research outcomes, encouraging investment and innovation.
(3) Regulatory Approval for AI-Based Medical Products: AI-enabled diagnostics, medical devices, and biotechnology products must comply with regulatory requirements before commercialisation.

(4) Clinical Trial and Research Regulations: AI applications used in clinical trials must adhere to ethical guidelines, informed consent requirements, and regulatory standards governing biomedical research.
(5) Cybersecurity and Data Security Compliance: Biotechnology firms must implement robust cybersecurity measures to comply with legal requirements protecting sensitive biological and healthcare data.
(6) AI Governance and Ethical Regulations: Emerging AI governance frameworks require organizations to ensure transparency, accountability, fairness, and responsible use of AI systems in biotechnology.
(7) Biological and Biosafety Regulations: AI-assisted biotechnology research involving genetically modified organisms (GMOs), pathogens, or biological materials must comply with biosafety and biosecurity laws.
(8) Cross-Border Data Transfer Regulations: International biotechnology collaborations require compliance with legal provisions governing the transfer, storage, and processing of biological and health data across borders.
(9) Liability and Accountability Frameworks: Clear legal provisions are needed to determine responsibility for errors, misdiagnoses, or adverse outcomes resulting from AI-based biotechnology applications.
(10) Compliance with Pharmaceutical and Biotechnology Standards: AI implementation must conform to national and international standards related to pharmaceutical manufacturing, quality assurance, laboratory practices, and biotechnology regulations to ensure safety, reliability, and legal compliance.

In conclusion, legal factors are pivotal to the successful adoption of AI in India's biotechnology industry. Data privacy regulations, intellectual property protections, and governance structures for AI-powered healthcare solutions guarantee that AI technologies function in a secure, ethical, and legally compliant setting.

12. RECOMMENDATIONS FOR STAKEHOLDERS REGARDING AI IMPLEMENTATION IN INDIA'S BIOTECHNOLOGY SECTOR :

(1) Government and regulatory authorities:

- **Create clear regulations:** Create well-defined and up-to-date policies and regulations for the use of AI in biotechnology, making sure they encompass data protection, intellectual property safeguards, safety requirements, and protocols for clinical trials.
- **Incentivize innovation:** provide tax incentives, grants, and subsidies for biotech companies investing in ai research and development to foster innovation.
- **Support ethical AI practices:** Establish ethical frameworks to regulate AI utilization in biotechnology, with a focus on gene editing and individualized medicine, to encourage responsible advancements and avoid improper applications.
- **Encourage collaboration between the public and private sectors:** Foster cooperation among government bodies, research organizations, and private biotechnology firms to speed up the integration of AI in drug discovery, diagnostic processes, and various other biotech uses.
- **Enhance infrastructure:** invest in infrastructure, such as high-performance computing resources and data storage systems, to facilitate ai adoption across the biotechnology sector.

(2) Biotechnology companies:

- **Invest in AI talent:** Attract and retain skilled professionals in ai, data science, and bioinformatics to ensure successful AI integration into research and development processes.
- **Focus on collaboration:** Collaborate with AI technology companies, universities, and healthcare providers to jointly create AI-driven solutions customized for the specific requirements of the biotechnology sector.
- **Adopt scalable AI solutions:** Adopt AI solutions that are scalable alongside business expansion, targeting key domains like drug development, diagnostic services, and tailored medical treatments.

- **Prioritize Data Protection and Security:** Emphasize safeguarding sensitive patient and genetic information by enforcing strong privacy protocols and adhering to regulations like the Personal Data Protection Bill.
- **Promote ethical AI use:** Guarantee the ethical use of AI technologies in biotechnology, especially in clinical decision-making that affects patient care and treatment results.

(3) Academic institutions and research organizations:

- **Develop AI research collaborations:** Partner with biotechnology companies to conduct research on AI applications in genomics, drug discovery, and other biotechnology sectors.
- **Curriculum development:** Update academic programs to include AI, bioinformatics, and biotechnology, ensuring that the next generation of professionals is prepared to work in AI-driven biotech environments.
- **Foster innovation hubs:** Create innovation centres or incubators that bring together AI experts, biotechnologists, and entrepreneurs to explore new applications of AI in biotechnology.
- **Encourage interdisciplinary research:** Promote research that combines AI biotechnology, ethics, and regulation, fostering an environment for balanced innovation and sustainable practices.

(4) Healthcare providers and clinicians:

- **Embrace AI integration:** Healthcare providers should adopt AI-driven tools in diagnostics and patient care, using aid to analyse medical data, enhance treatment planning, and provide personalized therapies.
- **Stay updated on AI developments:** Healthcare providers and medical experts should remain updated on emerging AI technologies and their uses in biotechnology to make well-informed choices in patient treatment.
- **Focus on training:** Provide training for healthcare professionals on the ethical use and understanding of ai-driven tools to ensure effective patient care while maintaining trust and transparency.

(5) Consumers and patients:

- **Be informed:** Consumers and patients ought to learn about the advantages and possible risks of AI technologies in biotechnology, particularly regarding genetic testing, AI-driven diagnostics, and tailored therapies.
- **Ensure informed consent:** Require clear communication and informed consent from biotechnology firms and healthcare professionals concerning the application of AI in genetic studies and medical care, with a focus on data privacy and protection.
- **Promote Ethical Standards and Practices:** consumers should advocate for ethical AI practices that prioritize their well-being, data protection, and accessibility to AI-driven healthcare solutions.

(6) Investors and venture capitalists:

- **Encourage AI investment:** Back and fund biotechnology firms incorporating AI into their workflows, recognizing the substantial potential of AI to foster innovation and expansion within the biotechnology sector.
- **Assess risk and reward:** Assess the benefits and challenges of funding AI-focused biotech startups by taking into account the regulatory landscape, possible market influence, and technological progress.
- **Promote long-term investment:** Encourage long-term investments in AI research and development, particularly in areas like personalized medicine, drug discovery, and genetic research, which are expected to see significant growth.

The successful adoption of AI in the Indian biotechnology industry requires collaboration and coordination across multiple stakeholders. Governments, biotech companies, academia, healthcare providers, and consumers must work together to foster innovation, ensure ethical practices, and create a supportive regulatory environment. By prioritizing workforce training, robust infrastructure, data protection, and ethical AI implementation, the sector can fully leverage AI's capabilities to advance biotechnology, enhancing healthcare quality and operational efficiency in India.

13. CONCLUSION :

In conclusion, AI is significantly transforming India's biotechnology sector, shifting it from traditional methods to data-driven approaches in drug discovery, genomics, and bioinformatics. This has led to faster innovation in diagnostics, personalized medicine, and biopharma, boosting India's global competitiveness. However, strong regulatory frameworks are essential to ensure ethical and safe use of AI in drug development and genetic engineering.

AI integration is also advancing genomic analysis, targeted therapies, agri-biotech, and bio-production. While adoption is growing, challenges like high costs, limited expertise, and data privacy remain. Larger pharma firms and agritech start-ups lead the way, highlighting the need for targeted investment and skill development across the industry.

A SWOC analysis of AI in the biotechnology sector reveals a multitude of opportunities alongside inherent challenges. AI's strengths, such as its ability to enhance R&D efficiency and accelerate drug discovery, make it a valuable asset in the industry's growth. However, weaknesses such as regulatory hurdles, data privacy issues, and high costs pose significant barriers to its widespread adoption. Opportunities abound in areas like clinical research, synthetic biology, and regenerative medicine, but challenges around ethical considerations, particularly in genetic data handling and algorithmic biases, must be addressed. The ABCD framework highlights the need to incorporate a variety of stakeholder viewpoints, aiming to enhance the advantages of AI while minimizing possible challenges for employees and the wider community.

Finally, the strategic recommendations derived from the pestle analysis point to the need for a comprehensive policy roadmap, investment strategies, and workforce readiness programs to ensure sustainable growth and innovation in the Indian biotechnology sector. Policymakers must prioritize ethical AI implementation, develop investment incentives, and create regulatory frameworks that foster AI-driven innovation. Investment opportunities for venture capitalists and biotech firms should focus on AI-enabled solutions, particularly in drug discovery, agricultural biotechnology, and healthcare innovations. Moreover, encouraging partnerships among biotechnology companies, AI ventures, and research institutions will be vital for enhancing AI technologies and keeping India leading in biotechnology advancements. As AI progresses, it is important for all parties involved to take a measured approach that minimizes risks while fully leveraging the opportunities this groundbreaking technology offers.

REFERENCES :

[1] Musaeva, B. (2023). The current state of the biotechnology market and its main development trends. In *BIO Web of Conferences* (Vol. 76, p. 04003). EDP Sciences. Google Scholar↗

[2] Pisano, G. P. (2006). *Science business: The promise, the reality, and the future of biotech*. Harvard Business Press. Google Scholar↗

[3] Mussatto, S. I., Dragone, G., Guimarães, P. M., Silva, J. P. A. Carneiro, L. M., Roberto, I. C., ... & Teixeira, J. A. (2010). Technological trends, global market, and challenges of bio-ethanol production. *Biotechnology advances*, *28*(6), 817-830. Google Scholar↗

[4] Sager, B. (2001). Scenarios on the future of biotechnology. *Technological Forecasting and Social Change*, *68*(2), 109-129. Google Scholar↗

[5] McKelvey, M. D., Rickne, A., & Laage-Hellman, J. (Eds.). (2004). *The economic dynamics of modern biotechnology*. Edward Elgar Publishing. Google Scholar↗

[6] Bhaskaran, E. (2022). The Performance of Pharma and Biotechnology Clusters in Tamil Nadu. *Productivity*, *62*(4).Google Scholar↗

[7] Camacho, M. J. S. M. (2024). *Globowarning-Mitigation of Globodera Spp: Outbreaks in Portugal Through an Innovative Early Nano-Detection System and Biocontrol* (Doctoral dissertation, Universidade de Evora (Portugal). Google Scholar↗

[8] Hermans, R. (2004). *International mega-trends and growth prospects of the Finnish biotechnology industry: essays on new economic geography, market structure of the pharmaceutical industry, sources of financing, intellectual capital and industry projections*. Helsinki University of Technology. Google Scholar↗

[9]. Cascelli, N. (2023). *Furan valorization through sustainable transformations using laccases and transaminases* (Doctoral dissertation).Google Scholar↗

[10] Safeena, M. I. S., & Zakeel, M. C. M. (2020). Nanobiotechnology-driven management of phytonematodes. *Management of phytonematodes: recent advances and future challenges*, 1-33. Google Scholar↗

[11] Kumar, N. K., Quach, U., Thorsteinsdóttir, H., Somsekhar, H., Daar, A. S., & Singer, P. A. (2004). Indian biotechnology—rapidly evolving and industry led. *Nature biotechnology*, *22*(Suppl 12), DC31-DC36. Google Scholar↗

[12] Uppal, A., Chakrabarti, R., Chirmule, N., Rathore, A., & Atouf, F. (2021). Biopharmaceutical industry capability building in India: report from a symposium. *Journal of Pharmaceutical Innovation*, 1-8. Google Scholar↗

[13] Panda, S., Singh, P. K., Mishra, S., Mitra, S., Pattnaik, P., Adhikary, S. D., & Mohapatra, R. K. (2023). Indian biosimilars and vaccines at crossroads–replicating the success of pharmagenerics. *Vaccines*, *11*(1), 110. Google Scholar↗

[14] Downs, J. B., & Velamuri, V. (2016). Business model innovation opportunities for the biopharmaceutical industry: A systematic review. *Journal of Commercial Biotechnology*, *22*(3). Google Scholar↗

[15] Konde, V. (2009). Biotechnology business models: An Indian perspective. *Journal of Commercial Biotechnology*, *15*, 215-226. Google Scholar↗

[16] Debnath, S., Seth, D., Pramanik, S., Adhikari, S., Mondal, P., Sherpa, D., ... & Mukerjee, N. (2024). A comprehensive review and meta-analysis of recent advances in biotechnology for plant virus research and significant accomplishments in human health and the pharmaceutical industry. *Biotechnology and Genetic Engineering Reviews*, *40*(4), 3193-3225. Google Scholar↗

[17] Rezaie, R., McGahan, A. M., Frew, S. E., Daar, A. S., & Singer, P. A. (2012). Emergence of biopharmaceutical innovators in China, India, Brazil, and South Africa as global competitors and collaborators. *Health Research Policy and Systems*, *10*, 1-13. Google Scholar↗

[18] Natesh, S., & Bhan, M. K. (2009). Biotechnology sector in India: strengths, limitations, remedies and outlook. *Current Science*, 157-169. Google Scholar↗

[19] Ramani, S. V. (2002). Who is interested in biotech? R&D strategies, knowledge base and market sales of Indian biopharmaceutical firms. *Research Policy*, *31*(3), 381-398. Google Scholar↗

[20] Hassan, M., Awan, F. M., Naz, A., deAndrés-Galiana, E. J., Alvarez, O., Cernea, A., ... & Kloczkowski, A. (2022). Innovations in genomics and big data analytics for personalized medicine and health care: a review. *International journal of molecular Sciences*, *23*(9), 4645. Google Scholar↗

[21] Ahmed, M. U., Saaem, I., Wu, P. C., & Brown, A. S. (2014). Personalized diagnostics and biosensors: a review of the biology and technology needed for personalized medicine. *Critical Reviews in Biotechnology*, *34*(2), 180-196. Google Scholar↗

[22] Verma, M. (2012). Personalized medicine and cancer. *Journal of personalized medicine*, *2*(1), 1-14. Google Scholar↗

[23] Imran, M. (2024). The Role of Biotechnology in Personalized Medicine: Current Trends and Future Directions. *Frontiers in Biotechnology and Genetics*, *1*(1), 18-36. Google Scholar↗

[24] Carrasco-Ramiro, F., Peiró-Pastor, R., & Aguado, B. (2017). Human genomics projects and precision medicine. *Gene therapy*, *24*(9), 551-561. Google Scholar↗

[25] Chan, I. S., & Ginsburg, G. S. (2011). Personalized medicine: progress and promise. *Annual review of genomics and human genetics*, *12*(1), 217-244. Google Scholar↗

[26] Strianese, O., Rizzo, F., Ciccarelli, M., Galasso, G., D'Agostino, Y., Salvati, A., ... & Rusciano, M. R. (2020). Precision and personalized medicine: how genomic approach improves the management of cardiovascular and neurodegenerative disease. *Genes*, *11*(7), 747. Google Scholar↗

[27] Lu, Y. F., Goldstein, D. B., Angrist, M., & Cavalleri, G. (2014). Personalized medicine and human genetic diversity. *Cold Spring Harbor perspectives in medicine*, *4*(9), a008581. Google Scholar↗

[28] Tutton, R. (2016). *Genomics and the reimagining of personalized medicine*. Routledge. Google Scholar↗

[29] Daniotti, S., & Re, I. (2021). Marine biotechnology: Challenges and development market trends for the enhancement of biotic resources in industrial pharmaceutical and food applications. A statistical analysis of scientific literature and business models. *Marine drugs*, *19*(2), 61. Google Scholar↗

[30] Silva, S. C., Ferreira, I. C., Dias, M. M., & Barreiro, M. F. (2020). Microalgae-derived pigments: A 10-year bibliometric review and industry and market trend analysis. *Molecules*, *25*(15), 3406. Google Scholar↗

[31] Chen, H., Qiu, T., Rong, J., He, C., & Wang, Q. (2015). Microalgal biofuel revisited: an informatics-based analysis of developments to date and future prospects. *Applied Energy*, *155*, 585-598. Google Scholar↗

[32] Pessôa, L. C., Deamici, K. M., Pontes, L. A. M., Druzian, J. I., & de Jesus Assis, D. (2021). Technological prospection of microalgae-based biorefinery approach for effluent treatment. *Algal Research*, *60*, 102504. Google Scholar↗

[33] Rumin, J., Nicolau, E., Gonçalves de Oliveira Junior, R., Fuentes-Grünewald, C., & Picot, L. (2020). Analysis of scientific research driving microalgae market opportunities in Europe. *Marine drugs*, *18*(5), 264. Google Scholar↗

[34] Lokko, Y., Heijde, M., Schebesta, K., Scholtès, P., Van Montagu, M., & Giacca, M. (2018). Biotechnology and the bioeconomy—Towards inclusive and sustainable industrial development. *New biotechnology*, *40*, 5-10. Google Scholar↗

[35] Haq, I. U., Chaudhry, W. N., Akhtar, M. N., Andleeb, S., & Qadri, I. (2012). Bacteriophages and their implications on future biotechnology: a review. *Virology journal*, *9*, 1-8. Google Scholar↗

[36] Bugge, M. M., Hansen, T., & Klitkou, A. (2016). What is the bioeconomy? A review of the literature. *Sustainability*, *8*(7), 691. Google Scholar↗

[37] Callegari, A., Bolognesi, S., Cecconet, D., & Capodaglio, A. G. (2020). Production technologies, current role, and future prospects of biofuels feedstocks: A state-of-the-art review. *Critical Reviews in Environmental Science and Technology*, *50*(4), 384-436. Google Scholar↗

[38] Liu, L., Li, H., Lazzaretto, A., Manente, G., Tong, C., Liu, Q., & Li, N. (2017). The development history and prospects of biomass-based insulation materials for buildings. *Renewable and Sustainable Energy Reviews*, *69*, 912-932. Google Scholar↗

[39] Costa, C., Fontes, M., & Heitor, M. V. (2004). A methodological approach to the marketing process in the biotechnology-based companies. *Industrial Marketing Management*, *33*(5), 403-418. Google Scholar↗

[40] Hulse, J. H. (2004). Biotechnologies: past history, present state and future prospects. *Trends in food science & technology*, *15*(1), 3-18. Google Scholar↗

[41] Festel, G. (2010). Industrial biotechnology: Market size, company types, business models, and growth strategies. *Industrial Biotechnology*, *6*(2), 88-94. Google Scholar↗

[42] Zambon, I., Colantoni, A., & Salvati, L. (2019). Horizontal vs vertical growth: Understanding latent patterns of urban expansion in large metropolitan regions. *Science of the Total Environment*, *654*, 778-785. Google Scholar↗

[43] Hotha, K. K. (2023). Unleashing the power of innovation in cdmos through customer-centricity and culture of service. *American Journal of Industrial and Business Management*, *13*(4), 234-246. Google Scholar↗

[44] Danzon, P. M., Epstein, A., & Nicholson, S. (2007). Mergers and acquisitions in the pharmaceutical and biotech industries. *Managerial and decision economics*, *28*(4-5), 307-328. Google Scholar↗

[45] Srinivas, S. (2004). *Technological learning and the evolution of the Indian pharmaceutical and biopharmaceutical sectors* (Doctoral dissertation, Massachusetts Institute of Technology). Google Scholar↗

[46] Sindelar, R. D. (2024). Genomics, other "OMIC" technologies, precision medicine, and additional biotechnology-related techniques. In *Pharmaceutical Biotechnology: Fundamentals and Applications* (pp. 209-254). Cham: Springer International Publishing. Google Scholar↗

[47] Goyal, I., & Yennappu, M. (2023). Institutionalization of personalized medicine in India: analysis of research trends and government interventions. *Personalized Medicine*, *20*(3), 283-297. Google Scholar↗

[48] Daud, H. M. (2004). Future Outlook of Agricultural Biotechnology in Malaysia. *Biotechnology and development: Challenges and opportunities for Asia*, 143. Google Scholar↗

[49] Festel, G. (2010). Industrial biotechnology: Market size, company types, business models, and growth strategies. *Industrial Biotechnology*, *6*(2), 88-94. Google Scholar↗

[50] Biswas, A. (2023). Commercial Status and Future Scope of Biobutanol Production from Biomass. *Production of Biobutanol from Biomass*, 283-300. Google Scholar↗

[51] Montague, C. T. (2008). *Developing a Strategy for a Centre of Competence for HIV Research and Development in South Africa* (Doctoral dissertation, University of Stellenbosch). Google Scholar↗

[52] Kumar, S., & Sharma, H. (2025). Disruptive Innovations using Tech-Business Analytics in the Quaternary Industry Sector. *Poornaprajna International Journal of Emerging Technologies (PIJET)*, *2*(2), 21-44. Google Scholar↗

[53] George, A. K., & George, S. M. SWOC Analysis of FDI in Health Care Industry of India. *Chinnu Mariam Chacko*, 1. Google Scholar↗

[54] Higson, S. (2015). *Peer Review Group Report School of Biotechnology 2 nd–4 th December 2015* (Doctoral dissertation, Dublin City University). Google Scholar↗

[55] Pramodini, S., Prajna, M., & Aithal, P. S. (2026). The Sweet Revolution: The Rise of the Chocolate Industry in India. *Poornaprajna International Journal of Teaching & Research Case Studies (PIJTRCS)*, *3*(1), 59-102. Google Scholar↗

[56] Singh, A. V., & Sadhanandan, H. D. (2025). India's sustainable roadmap towards Viksit Bharat@ 2047-an inclusive SWOC analysis. *management*, *12*, 8782. Google Scholar↗

[57] Dahiya, S., & Garg, M. (2024). Potential of nutritious Indian medicinal plants to boost immunity in the aftermath of pandemics: A SWOC analysis. *Recent Progress in Nutrition*, *4*(1), 1-20. Google Scholar↗

[58] Hanafi, S., & Arvanitis, R. (2013). Strengths and weaknesses of science and technology institutions in Arab countries. *Escwa Technology Centre*. Google Scholar↗

[59] Radha, P., & Aithal, P. S. (2024). ABCD Analysis of Stakeholder Perspectives on the Conceptual Model: Unveiling Synergies between Digital Transformation and Organizational Performance in Manufacturing. *International Journal of Applied Engineering and Management Letters (IJAEML)*, *8*(1), 15-38. Google Scholar↗

[60] Aithal, P. S. (2016). Study on ABCD analysis technique for business models, business strategies, operating concepts & business systems. *International Journal in Management and Social Science, 4*(1), 95-115. Google Scholar↗

[61] Aithal, P. S., Shailashree, V. T., & Kumar, P. M. (2015). A new ABCD technique to analyse business models & concepts. *International Journal of Management, IT and Engineering, 5*(4), 409-423. Google Scholar↗

[62] Aithal, P. S. (2017). ABCD Analysis as Research Methodology in Company Case Studies. *International Journal of Management, Technology, and Social Sciences (IJMTS), 2*(2), 40-54. Google Scholar↗

[63] Aithal, P. S., Shailashree, V., & Kumar, P. M. (2015). Application of ABCD Analysis Model for Black Ocean Strategy. *International journal of applied research, 1*(10), 331-337. Google Scholar↗

[64] Aithal, A., & Aithal, P. S. (2017). ABCD analysis of task shifting–an optimum alternative solution to professional healthcare personnel shortage. International Journal of Health Sciences and Pharmacy (IJHSP), 1(2), 36-51. Google Scholar↗

[65] Aithal, S., & Aithal, P. S. (2016). ABCD analysis of Dye-doped Polymers for Photonic Applications. *IRA-International Journal of Applied Sciences, 4*(3), 358-378. Google Scholar↗

[66] Raj, K., & Aithal, P. S. (2018). Generating Wealth at the Base of the Pyramid–a Study Using ABCD Analysis Technique. *International Journal of Computational Research and Development (IJCRD), 3*(1), 68-76. Google Scholar↗

[67] Aithal, P. S., Shailashree, V., & Kumar, P. M. (2016). The study of the new national institutional ranking system using ABCD framework. *International Journal of Current Research and Modern Education (IJCRME), 1*(1), 389-402. Google Scholar↗

[68] Shenoy, V., & Aithal, P. S. (2016). ABCD Analysis of On-line Campus Placement Model. *IRA-International Journal of Management & Social Sciences, 5*(2), 227-244. Google Scholar↗

[69] Lane, T. S., Rempe, C. S., Davitt, J., Staton, M. E., Peng, Y., Soltis, D. E., ... & Stewart Jr, C. N. (2016). Diversity of ABC transporter genes across the plant kingdom and their potential utility in biotechnology. *BMC biotechnology*, *16*(1), 47. Google Scholar↗

[70] Aithal, P. S., & Aithal, S. (2024). An overview of the use of ICCT and nanotechnology in yellow economy: Current status and future opportunities. *Poornaprajna International Journal of Emerging Technologies (PIJET)*, *1*(1), 29-62. Google Scholar↗

[71] Aithal, P. S. Leveraging Industry 5.0 Technologies to Realize the United Nations Sustainable Development Goals. Google Scholar↗

[72] Aithal, A. (2025). Strategic Evaluation of Bio-Active Composite Therapy (BACT) and Stem Cell Augmentation in Regenerative Orthopedics: A Multi-Framework Exploratory Review for 2026 and Beyond. *Poornaprajna International Journal of Basic & Applied Sciences (PIJBAS)*, *2*(2), 100-118. Google Scholar↗

[73] Aithal, P. S., & Aithal, S. (2023). Incubationship–A systematic analysis of recently announced super innovation in higher education using SWOC, ABCD, and PESTL frameworks. *International Journal of Case Studies in Business, IT, and Education (IJCSBE)*, *7*(4), 48-90. Google Scholar↗

[74] Agrafiotis, D. K., Alex, S., Dai, H., Derkinderen, A., Farnum, M., Gates, P., ... & Yao, X. (2007). Advanced biological and chemical discovery (ABCD): centralizing discovery knowledge in an inherently decentralized world. *Journal of Chemical Information and Modeling*, *47*(6), 1999-2014. Google Scholar↗

[75] Cotet, G. B., Balgiu, B. A., & Zaleschi, V. C. (2017). Assessment procedure for the soft skills requested by Industry 4.0. In *MATEC web of conferences* (Vol. 121, p. 07005). EDP Sciences. Google Scholar↗

[76] Davies, K. (2007). ABCD: The Relentless Pursuit of Perfection. *Bio-IT World*, *6*(9). Google Scholar↗

[77] Aithal, P. S., & Aithal, S. (2018). Factor & Elemental Analysis of Nanotechnology as Green Technology using ABCD Framework. *International Journal of Management, Technology, and Social Sciences (IJMTS)*, *3*(2), 57-72. Google Scholar↗

[78] Aithal, P. S. (2021). Analysis of systems & technology using ABCD framework. *Chapter*, *8*, 345-385. Google Scholar↗

[79] Poojary, S., & Aithal, P. S. (2026). Strategic Leadership and Vision: An In-Depth CEO Analysis of Zerodha and Founder-CEO Nithin Kamath. *Poornaprajna International Journal of Teaching & Research Case Studies (PIJTRCS)*, *3*(1), 220-244. Google Scholar↗

[80] Shenoy, C. G., & Aithal, P. S. (2026). Edge Computing Industry Analysis: Business Models, Technological Innovations, and Future Opportunities in the Era of AI and 5G. *Poornaprajna International Journal of Teaching & Research Case Studies (PIJTRCS)*, *3*(1), 386-428. Google Scholar↗

[81] Devadiga, D., & Aithal, P. S. (2026). Strategic Diversification: A Path to New Market Leadership for Britannia Industries Ltd. *Poornaprajna International Journal of Teaching & Research Case Studies (PIJTRCS)*, *3*(1), 366-385. Google Scholar↗

[82] Devadiga, I., & Aithal, P. S. (2026). CEO Analysis of Sanjiv Puri of ITC Limited: A Multi-Framework Evaluation of Technology-Led Leadership, Strategic Diversification, and Sustainable Transformation. *Poornaprajna International Journal of Teaching & Research Case Studies (PIJTRCS)*, *3*(1), 260-291. Google Scholar↗

[83] Manwitha, N., & Aithal, P. S. (2026). Strategic Leadership, Digital Transformation, and Organizational Excellence: A CEO Analysis of Dinesh Kumar Khara at State Bank of India. *Poornaprajna International Journal of Teaching & Research Case Studies (PIJTRCS)*, *3*(1), 482-516. Google Scholar↗

[84] Devadiga, D., & Aithal, P. S. (2026). Architecting Intelligence: An Integrated Framework Analysis of Jensen Huang's Transformational Leadership at NVIDIA Corporation. *Poornaprajna International Journal of Teaching & Research Case Studies (PIJTRCS)*, *3*(1), 292-329. Google Scholar↗

[85] Pramodini, S., & Aithal, P. S. (2026). CEO Analysis of Mark Zuckerberg of Meta Company Limited. *Poornaprajna International Journal of Teaching & Research Case Studies (PIJTRCS)*, *3*(1), 330-365. Google Scholar↗

[86] Devadiga, D., & Aithal, P. S. (2026). Generative AI in the Marketing Industry: An Industry Analysis of Content Transformation, Consumer Engagement, and Firm Performance. *Poornaprajna International Journal of Management, Education & Social Science (PIJMESS)*, *3*(1), 220-248. Google Scholar↗

[87] Adarsh Aithal (2026). The Internet of Orthopaedic Things (IoOT): A Multi-Framework Strategic Analysis of Smart Implants, Market Dynamics, and Future Research Frontiers. (2026). *Poornaprajna International Journal of Basic & Applied Sciences (PIJBAS)*, *3*(1), 1-28. Google Scholar↗

[88] Adarsh Aithal (2026). Exploratory Analysis on Computer-Assisted Smart Spine Surgery using AR/VR Technology through Remote Telesurgery via 5G/6G. (2026). *Poornaprajna International Journal of Basic & Applied Sciences (PIJBAS)*, *3*(1), 29-64. Google Scholar↗

[89] Mehta, A., Niaz, M., Adetoro, A., & Nwagwu, U. (2024). Advancements in manufacturing technology for the biotechnology industry: The role of artificial intelligence and emerging trends. *International Journal of Chemistry, Mathematics and Physics*, *8*(2), 12-18. Google Scholar↗

[90] Kumar, K., Sharma, R., Ranjan, K., & Pandey, D. K. (2025). Artificial Intelligence in Biotechnology. In *Artificial Intelligence and Biological Sciences* (pp. 192-218). CRC Press. Google Scholar↗

[91] Gomes, A., Gonçalves, B., Inglês, B., Silvério, S., Pinto, C. A., & Saraiva, J. A. (2024). Potential impacts of artificial intelligence (AI) in biotechnology. *Applied Sciences*, *14*(24), 11801. Google Scholar↗

[92] Ali, M., Shabbir, K., Ali, S., Mohsin, M., Kumar, A., Aziz, M., ... & Sultan, H. M. (2024). A new era of discovery: how artificial intelligence has revolutionized the biotechnology. *Nepal Journal of Biotechnology*, *12*(1), 1-11. Google Scholar↗

[93] Phillip, A. (2026). The Role of Artificial Intelligence in Modern Biotechnology: A Comprehensive Review. *Journal of Applied Biotechnology Reports*, *13*(1), 1899-1921. Google Scholar↗

[94] Sharma, P., & Singh, S. (2026). AI-nanotech synergies: recent advances in sustainable bio-manufacturing. *World Journal of Microbiology and Biotechnology*, *42*(7), 332. Google Scholar↗

[95] Takeda, H. (2025). The Impact of Artificial Intelligence on Biotechnological Research and Development. *Journal of Commercial Biotechnology*, *30*(2), 177-187. Google Scholar↗

[96] DSVNM, R., Rahul, G., & SVGVA, P. (2024). AI and machine learning in biotechnology: a paradigm shift in biochemical innovation. *International Journal of Plant, Animal and Environmental Sciences*, *14*(4), 70-80. Google Scholar↗

[97] Spencer, J. W. (2025). The Role of Artificial Intelligence in Accelerating Biotechnology Product Development. *Journal of Commercial Biotechnology*, *30*(3), 256-266. Google Scholar↗

[98] Artico, F., Edge III, A. L., & Langham, K. (2022). The future of artificial intelligence for the BioTech big data landscape. *Current opinion in biotechnology*, *76*, 102714. Google Scholar↗

[99] Nagamarpalli, R. S. (2021). Biotechnology and AI. *Issue 3 Int'l JL Mgmt. & Human.*, *4*, 4035. Google Scholar↗

[100] Oyeniran, K. A., Oyeniran, O. H., & Oladunmoye, K. M. (2025). Artificial Intelligence, Innovation, and Safety in Biotechnology Research. In *Cases on AI Innovations in Occupational Health and Safety* (pp. 73-98). IGI Global Scientific Publishing. Google Scholar↗

[101] Alaa, N., Hesham, M., Attia, M., Kamal, R., Alhammad, S. A., Ibrahim, D., ... & Gomaa, A. E. (2025). The Role of Agentic AI in Revolutionizing Biotechnology: An Overview. *International Journal for Biotech Research and Innovations*, 1-18. Google Scholar↗

[102] Izankar, S. V., Kumar, P., & Waghmare, G. (2024, December). Evolution of artificial intelligence in biotechnology: from discovery to ethical and beyond. In *AIP Conference Proceedings* (Vol. 3188, No. 1, p. 080037). AIP Publishing LLC. Google Scholar↗

[103] Popović, V., Bošković, J., Filipović, A., & Popović, M. (2024). Application of artificial intelligence (AI) in biotechnology and medicine. *Limes plus*, *20*(2-3), 43-71. Google Scholar↗

[104] Holzinger, A., Keiblinger, K., Holub, P., Zatloukal, K., & Müller, H. (2023). AI for life: Trends in artificial intelligence for biotechnology. *New biotechnology*, *74*, 16-24. Google Scholar↗

[105] Sharma, D., & Singh, K. (2025). AI-enhanced bioprocess technologies: machine learning implementations from upstream to downstream operations. *World Journal of Microbiology and Biotechnology*, *41*(8), 278. Google Scholar↗

[106] Laith, A. E., Jaouni, H., & Mihyar, A. (2025). Addressing cyberbiosecurity challenges in the modern era of biotechnology and artificial intelligence: cyberbiosecurity in the age of biotechnology and AI. *Global Biosecurity*. Google Scholar↗

[107] Ashfi, S. A. (2024). Ethical implications of emerging technologies: A comparative analysis of AI, biotechnology, and robotics. *Journal of Research and Innovation in Technology and Management (JRITM)*, *1*(1). Google Scholar↗

[108] Morita, P. P., Abhari, S., Kaur, J., Lotto, M., Miranda, P. A. D. S. E. S., & Oetomo, A. (2023). Applying ChatGPT in public health: a SWOT and PESTLE analysis. *Frontiers in Public Health, 11*(1), 1225861. Google Scholar↗

[109] Rastogi, N., & Trivedi, M. K. (2016). PESTLE technique–a tool to identify external risks in construction projects. *International Research Journal of Engineering and Technology (IRJET), 3*(1), 384-388. Google Scholar↗

[110] Capobianco, N., Basile, V., Loia, F., & Vona, R. (2021). Toward a sustainable decommissioning of offshore platforms in the oil and gas industry: A PESTLE analysis. *Sustainability, 13*(11), 6266. Google Scholar↗

[111] Günther, E., & Hüske, A. K. (2015). How stakeholder shape innovation in controversial industries: the biotechnology industry in Germany. *uwf Umwelt Wirtschafts Forum*, *23*(3), 77-86. Google Scholar↗

[112] Knoebl, M., Fazeni-Fraisl, K., Lindorfer, J., Puschnigg, S., Friedl, C., & Mueller, C. (2026). Going beyond quantification: applying a multidimensional qualitative analysis approach to support decision making for sustainable biorefinery deployment—a case study. *Clean Technologies and Environmental Policy*, *28*(6), 165. Google Scholar↗

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