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DISRUPTIVE INNOVATIONS IN BIOTECHNOLOGY AND THE EMERGENCE OF THE BIOECONOMY: POLICY IMPLICATIONS AND STRATEGIC CONSIDERATIONS

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Warsaw, April 2025

DISRUPTIVE INNOVATIONS IN BIOTECHNOLOGY AND THE EMERGENCE OF THE BIOECONOMY: POLICY IMPLICATIONS AND STRATEGIC CONSIDERATIONS

Introduction

Creative destruction, a concept introduced by economist Joseph Schumpeter in 1942, describes the process by which new innovations replace outdated technologies and industries. This process involves the dismantling or transformation of existing systems and infrastructures by breakthrough innovations that pave the way for new industries and opportunities. Schumpeter emphasized that creative destruction is vital to economic development, as the introduction of new products or technologies renders older ones obsolete. In this context, biotechnology plays a pivotal role, with emerging bio-based solutions - such as biofuels, bio-based plastics, bioenergy, and biobased fibers and others - replacing conventional fossil-based technologies. These innovations disrupt industries and markets, promoting sustainable development while addressing pressing environmental challenges.

The **primary aim of this study** is to examine the role of creative destruction within the sectors and industries influenced by biotechnology, focusing on how biotech-driven solutions can supplant conventional products and technologies. To achieve this, several key questions must be addressed: *What are the primary drivers that accelerate the transition to biotechnology-driven solutions? What are the barriers hindering the creative destruction process within the industries and sectors affected by the biotechnology? When can we expect the widespread adoption of biobased products and transition to bioeconomy? What are the policy implications that could facilitate this transition and overcome these obstacles?* These questions will offer insights into the timing, conditions, and challenges necessary for biotechnology to fully replace conventional technologies.

The paper is structured in four sections, each of which progressively builds upon these questions and provides a framework for understanding the role of biotechnology in industrial and systemic creative destruction processes. The first section explores current trends in biotechnology, analyzing how bio-based solutions are reshaping various sectors and shedding light on their market potential and adoption rates. The second section draws on the concept of Kondratiev's long waves to examine the cyclical nature of technological innovation and discuss how biotechnology fits into the broader pattern of industrial transformation. The third section identifies key drivers - such as technological advancements, economic incentives, and policy frameworks - that are accelerating

the transition to a bio-based economy. It also discusses the barriers, including regulatory challenges and market resistance, that hinder the widespread adoption of bio-solutions. Finally, the paper ends with conclusions and policy implications, which synthesizes the findings and provides policy recommendations.

2. Biotechnology and the Rise of Bio-Solutions: An Analysis of Trends and Market Influence

The unprecedented rise of biotechnology in recent years is reshaping industries and driving sustainable growth across the globe. Central to this transformation are a number of key factors that are accelerating the transition to biotechnology-driven solutions. Technological advancements, such as breakthroughs in genetic engineering, CRISPR¹, and synthetic biology, have unlocked new frontiers in fields ranging from healthcare to agriculture and environmental sustainability. These innovations are enabling more precise and efficient solutions to address some of the world's most pressing challenges.

Environmental sustainability stands as one of the primary catalysts, as increasing awareness of climate change, resource depletion, and biodiversity loss is pushing for green alternatives. Biotechnology offers promising solutions, such as bio-based materials, renewable energy, and waste-to-resource processes, which are contributing to a more sustainable future. The section below discusses some of the leading outcomes of biotechnology.

Bioplastics

Bioplastics currently account for approximately 0.5% of the 414 million tonnes of plastic produced annually. Despite the continued rise in global plastic production due to increasing demand and technological advancements, the bioplastics sector is not expanding rather slowly. As Nova Institute (2024) predicts production capacity is expected to grow from 2.47 million tonnes in 2024 to 5.73 million tonnes by 2029. This growth is driven by material innovation, increasing awareness of sustainability, and the rising demand for environmentally friendly alternatives to conventional plastics. Bioplastics now offer viable alternatives for nearly all conventional plastic materials and their applications. The sector is driven by advancements in biobased and biodegradable polymers, such as polylactic acid (PLA), polyhydroxyalkanoates (PHA), and biobased polyethylene (PE). Additionally, biobased polypropylene (PP) is steadily gaining market share, further contributing to

¹ CRISPR (Clustered Regularly Interspaced Short Palindromic Repeats), is a revolutionary technology that allows scientists to precisely edit DNA.

future capacity increases. These innovations enhance the functionality of bioplastics, making them more competitive in industries traditionally dominated by fossil-based plastics. The development of new materials and the diversification of bioplastic applications suggest a strong market trajectory. As companies invest in research and production capabilities, more sustainable solutions are expected to replace conventional plastics, fostering a circular economy and reducing environmental impact. Bioplastics are increasingly used across various industries, including packaging, textiles, consumer goods, automotive, and agriculture. Packaging remains the dominant market segment, representing 45% of the total bioplastics market (1.12 million tonnes) in 2024. The versatility of bioplastics allows their use in a broad range of products, from compostable bags and food containers to automotive components and medical devices. This growing adoption underscores the demand for sustainable alternatives across multiple industries. In 2024, the bioplastics industry is operating at an average of 58% capacity, with 1.44 million tonnes produced out of the 2.47 million tonnes available. However, utilization rates vary significantly by polymer type, ranging between 35% and 100%. While some bioplastic types experience full-scale production, others face supply chain and technological challenges that limit their current output. Optimizing production efficiency and expanding manufacturing capabilities will be crucial to meeting the increasing demand for bioplastics. As infrastructure improves and investments in the sector continue, the gap between production capacity and actual production is expected to narrow, facilitating further growth in the industry. The 2024 market data update has been compiled with the expertise of the nova-Institute (Hürth, Germany), providing key insights into the sector's development and future trends. These findings highlight the potential of bioplastics as a sustainable alternative to conventional plastics, reinforcing the importance of continued investment, innovation, and policy support to accelerate their adoption worldwide.

Figure 1. Production capacities of bioplastics



Global production capacities of bioplastics in 1,000 tonnes

Source: European Bioplastics, nova-Institute (2024)

These findings highlight the potential of bioplastics as a sustainable alternative to conventional plastics, reinforcing the importance of continued investment, innovation, and policy support to accelerate their adoption worldwide.

The growing interest in bioplastics as a sustainable alternative to conventional plastics highlights the need for continued innovation and investment. Companies like Interface (www.interface.com), NatureWorks (www.natureworksllc.com), and Stora Enso (www.storaenso.com) have been pivotal in advancing bio-based solutions over the past few decades. Interface transitioned to bio-based materials in the 2000s to 2010s, focusing on reducing its environmental footprint in the flooring industry. NatureWorks, founded in 2003, has been at the forefront of producing bio-based plastics, particularly through its Ingeo brand, made from renewable plant-based resources. Similarly, Stora Enso shifted towards bio-based solutions in the mid-2000s to 2010s, positioning itself as a leader in renewable materials and bio-based plastics. These companies exemplify how the bioplastics sector is gaining momentum, with ongoing advancements contributing to a more sustainable future. Their actions reinforce the importance of continued policy support and innovation to accelerate the global adoption of bioplastics as a viable alternative to traditional petroleum-based plastics.

Biofuels

Global biofuel production reached over 130 billion liters in 2022, with projections for growth as technologies improve. In 2023, global biofuel production reached approximately 960 thousand

barrels of oil equivalent per day, marking a significant increase from the 12 thousand barrels per day produced in 2000.



Figure 2. Biofuel production worldwide from 2000 to 2023 (in 1,000 barrels of oil equivalent per day)

This expansion has been primarily driven by policy measures promoting biofuel production and utilization, motivated by the potential for enhanced energy security and reductions in greenhouse gas emissions. The environmental benefits of biofuels stem from their lower carbon footprint relative to fossil fuels, as well as their capacity to utilize waste materials that would otherwise be discarded. Various regulatory mechanisms, including blending mandates, sustainability criteria, fuel quality standards, and import tariffs, have influenced the biofuel market's growth and structure. Projections indicate that the global biofuels market will exceed a valuation of 200 billion USD by 2030.

Bioethanol and biodiesel represent the two most widely produced and utilized biofuels. Bioethanol is synthesized from carbohydrate-based feedstocks, such as cellulose biomass, with coarse grains and sugarcane serving as the predominant raw materials, though regional variations exist. Biodiesel, in contrast, is derived from lipid-based feedstocks, including vegetable oils and animal fats. Additionally, the increasing use of non-agricultural feedstocks, such as waste oils and residual

Details: Worldwide; Kearney; KPMG; 2000 to 2023

fats, has gained relevance, particularly in regions like the United States and Europe, contributing to a more diversified and sustainable biofuel supply chain.

Several companies are making significant strides in the biofuels industry, promoting sustainability and reducing carbon emissions. Poet LLC, one of the largest U.S. biofuels producers, specializes in ethanol production and operates numerous plants focused on sustainability (www.poet.com). Renewable Energy Group (REG) leads in biodiesel and renewable diesel production, utilizing feedstocks like vegetable oils and waste oils (www.reg.com). Green Plains Inc. is a key bioethanol producer, using advanced technologies to improve biofuel efficiency (www.greenplains.com). Neste produces renewable diesel and sustainable aviation fuel (SAF) from waste and residues, focusing on low-carbon alternatives (www.neste.com). Sustainable Energy Solutions (SES) develops biodiesel and bioethanol, with an emphasis on reducing fossil fuel dependence (www.sustainableenergy.com). These companies are driving innovation and shaping the biofuels market with sustainable alternatives to fossil fuels.

Bioenergy

Bioenergy, derived from biological sources such as plant and animal materials, plays a crucial role in the global transition to renewable energy. Its share in global renewable energy consumption has steadily increased in recent years, reaching approximately 10% (International Energy Agency, IEA, 2025). This growth is driven by the increasing demand for cleaner energy solutions to mitigate climate change and reduce reliance on fossil fuels.

The bioenergy market has experienced remarkable expansion, driven by increasing investments in renewable energy infrastructure and the growing demand for sustainable energy solutions. In 2024, the market was valued at approximately USD 144.99 billion and is projected to surpass USD 299.44 billion by 2034, reflecting a strong compound annual growth rate of 7.52% over the forecast period. North America has emerged as the dominant regional player, accounting for the largest market share in 2024. Within the product segments, solid biomass led the market, while wood and woody biomass contributed the highest revenue share among feedstock categories (Figure 3).



Figure 3. Bioenergy market size 2024 - 2034 (in billions of USD)

While North America currently leads the global bioenergy sector, the Asia-Pacific region is expected to experience the highest growth rate in the coming years. Many countries within this region face challenges related to electricity shortages due to underdeveloped generation infrastructure. The increasing demand for electricity, coupled with rising government investments in bioenergy research and development, is driving significant growth in this market. The US plays a crucial role in shaping the bioenergy landscape in North America, with its market valued at USD 46.13 billion in 2024 and expected to nearly double to USD 99.83 billion by 2034, growing at a rate of 8.03% annually (Figure 4). The rapid expansion of bioenergy in this region is fuelled by substantial investments in energy infrastructure, government support for renewable initiatives, and the active participation of major industry players in advancing bioenergy technologies.

Source: https://www.precedenceresearch.com/bioenergy-market





Source: https://www.precedenceresearch.com/bioenergy-market

Bioenergy is utilized across various sectors, including electricity generation, heating, and transportation. In the industrial sector, bioenergy consumption is projected to rise significantly, from over 11 exajoules (EJ) of energy in 2023 (6% of energy use) to nearly 17 EJ (9.4%) by 2030. This increase is particularly evident in industries such as pulp and paper, food and tobacco, and non-metallic minerals (IEA, 2025).

The bioenergy market continues to attract significant investments, with major oil and gas companies increasingly focusing on biofuels, especially sustainable aviation fuel (SAF). By 2030, 43 projects are anticipated to add production capacities of up to 286,000 barrels per day. However, this growth also raises environmental concerns, such as deforestation in regions like Indonesia to meet biomass energy demand, emphasizing the need for sustainable bioenergy production practices (Reuters; AP News).

In conclusion, bioenergy is a key player in the global shift toward renewable energy, with strong market growth and regional significance. Ensuring sustainable production and consumption practices is essential to fully harness its potential while addressing the environmental challenges associated with its expansion.

Bio-based chemicals

The development of bio-based chemicals, including solvents, adhesives, and coatings, is gaining significant momentum as industries seek sustainable alternatives to petroleum-based products. This shift is driven by growing environmental concerns, regulatory pressures, and the desire to reduce dependence on fossil fuels. As a result, many companies in the household care and chemical industries, such as Seventh Generation (https://www.seventhgeneration.com), have transitioned to 100% bio-based formulations and use recycled, eco-friendly packaging. Seventh Generation has gained significant market share in the eco-friendly segment, promoting health, safety, and sustainability. The company also aims for carbon neutrality and 100% renewable energy in its operations, aligning with the broader bio-based product movement.

The global bio-based adhesives market is experiencing notable growth. In 2021, the market was valued at approximately USD 5.27 billion and is projected to reach USD 7.00 billion by 2027, growing at a compound annual growth rate (CAGR) of 4.85% during the forecast period. This growth is fuelled by evolving emission regulations, rapid industrialization in emerging economies, and stringent policies limiting the use of formaldehyde in wood panels. Bio-based adhesives, derived from natural sources such as proteins, lignin, natural resins, vegetable oils, and starch, play a crucial role in reducing environmental impact by preventing the release of harmful chemicals and meeting stringent government standards related to carbon emissions (www.prnewswire.com/news-releases/bio-based-adhesives, 2025).

As a result many companies in household care and chemical sector like Seventh Generation (https://www.seventhgeneration.com) has transitioned to 100% bio-based formulations and uses recycled, eco-friendly packaging. It has gained significant market share in the eco-friendly segment, promoting health, safety, and sustainability. Seventh Generation aims for carbon neutrality and 100% renewable energy in its operations, aligning with the bio-based product movement. Other companies that have made the most noticeable shift from conventional chemicals to bio-based solutions include Ecover (www.ecover.com), Method (www.methodhome.com), Biokleen (www.biokleenhome.com), Dr. Bronner's (www.drbronner.com), and Branch Basics (www.branchbasics.com). These companies are at the forefront of the bio-based movement, offering products made from natural and plant-derived ingredients. Others, like The Honest Company (www.honest.com) and Melaleuca (www.melaleuca.com), emphasize non-toxic and eco-friendly ingredients but may still use some conventional chemicals in their formulations.

The packaging industry is a significant consumer of bio-based adhesives, driven by increasing demand for sustainable packaging solutions. In 2025, the bio-based adhesives market is estimated

at 1.21 million tons, with projections indicating growth to 1.54 million tons by 2030, at a CAGR of 5.00%. Europe currently dominates this market, with expectations of continued growth during the forecast period (www.mordorintelligence.com/industry-reports, 2025).

Other examples include the BMW Group (www.bmwgroup.com) shifting to bio-based materials in the late 2000s to early 2010s, Aveda (www.aveda.com) began focusing on bio-based ingredients and sustainable packaging around the 2000s to 2010s, Interface (www.interface.com) transitioning to bio-based materials in the 2000s to 2010s, NatureWorks (www.natureworksllc.com) focusing on bio-based plastics since its founding in 2003, or Stora Enso (www.storaenso.com) moving towards bio-based solutions in the mid-2000s to 2010s.

While specific global statistics for bio-based solvents and coatings are less readily available, the overall trend indicates a growing market. The increasing adoption of bio-based adhesives suggests a parallel rise in demand for other bio-based chemicals, including solvents and coatings, as industries continue to seek environmentally friendly alternatives. The development and adoption of bio-based solvents, adhesives, and coatings represent a significant step toward more sustainable industrial and consumer practices. The push for sustainability, coupled with regulatory support, is expected to drive further growth in these sectors, although detailed market analyses are needed to quantify this expansion accurately.

Other bio-based products

Bio-based textiles, derived from renewable biological resources such as plants and animals, represent a significant segment within the broader bio-based products industry. These textiles include natural fibers like cotton, wool, silk, and linen, as well as innovative materials produced from sources like polylactic acid (PLA) and polyhydroxyalkanoates (PHA). The global market for bio-based fibers has been experiencing substantial growth. In 2023, the market was valued at approximately USD 41.39 billion and is projected to reach USD 203.99 billion by 2030, reflecting a compound annual growth rate (CAGR) of 25.62% during the forecast period. This expansion is driven by increasing consumer demand for sustainable products, heightened environmental awareness, and the need to reduce reliance on fossil fuels (Verified Market Reports).

Regarding market valuations and growth projections, various sources provide differing figures. For instance, FactMR estimates the global bioplastic textiles market to be valued at approximately USD 915.6 million in 2023, projecting it to reach USD 2,128.1 million by 2033, reflecting a compound annual growth rate (CAGR) of 8.8% during that period (<u>FactMR</u>, 2023). Similarly, Coherent

Market Insights anticipates the biodegradable fabrics market to grow from USD 5.88 billion in 2025 to USD 13.65 billion by 2032, indicating a CAGR of 12.8% (Coherent Market Insights, 2025).

In the European Union, the bio-based textiles sector has demonstrated notable economic significance. In 2021, it provided employment to approximately 700,000 individuals and contributed EUR 25 billion in added value. Key factors enabling the sector's growth in the EU include strengthening and upscaling local value chains, identifying and promoting sustainable biomass feedstock sources, and supporting innovation (knowledge4policy.ec.europa.eu). The market is also witnessing a rise in bio-based synthetic fibers such as PLA and polytrimethylene terephthalate (PTT), offering sustainable alternatives to traditional petroleum-based synthetics like polyester. The broader sustainable fabrics market, which encompasses bio-based textiles, was valued at USD 26.45 billion in 2022 and is expected to register a steady CAGR of 13.3%, reaching USD 92.46 billion by 2032. This growth is attributed to the rapid expansion of the textile industry in emerging markets and increasing awareness of sustainable material technologies (GlobeNewswire, 2023). The good example of successful transition to bio-based textile is Lenzing AG (www.lenzing.com) adopting bio-based textiles in the late 2000s to early 2010s,

In summary, bio-based textiles constitute a vital component of the bio-based products industry, with a robust growth trajectory observed globally and regionally. The sector's expansion is fueled by technological innovations, supportive policies, and a collective shift towards sustainability in the textile industry.

2. Kondratiev's Long Waves and the Role of Biotechnology in the Sixth Wave

In understanding the disruptive nature of innovations, two theories are particularly important: Kondratiev's long waves and Schumpeter's concept of creative destruction. Both theories provide insights into how technological advancements can reshape economies and industries over long periods.

Nikolai Kondratiev, a Russian economist, introduced the theory of long waves, or Kondratiev waves, in the 1920s. His theory posits that capitalist economies experience long-term cycles of economic boom followed by periods of depression, each lasting approximately 50 to 60 years. These waves are primarily driven by technological innovations that disrupt existing industries and create new ones, leading to major shifts in economic structures. Kondratiev's theory suggests that each wave is marked by a dominant technological innovation that drives economic growth and

transformation. For example, the first Kondratiev wave, starting in the late 18th century, was driven by the Industrial Revolution, characterized by the rise of steam power and mechanized manufacturing (Superbusinessmanager.com, Investopedia, 2021).

Joseph Schumpeter, an Austrian economist, introduced the concept of "creative destruction" in his 1942 work *Capitalism, Socialism and Democracy*. Schumpeter argued that capitalist economies evolve through a process of continual innovation, where new technologies and business models replace outdated ones, thereby "destroying" existing industries but also creating new opportunities for growth and development. According to Schumpeter, innovation is the driving force of economic growth, but it also leads to the obsolescence of older technologies, businesses, and industries. Creative destruction is a disruptive process that can result in temporary instability but ultimately drives long-term economic progress (Schumpeter, 1942). The intersection of these two theories—Kondratiev's long waves and Schumpeter's creative destruction—offers a compelling framework for understanding how innovations disrupt existing economic systems The second Kondratiev wave, emerging around 1850, was propelled by the advent of steam power and railways, which revolutionized transportation and manufacturing, leading to significant economic expansion. The third and fourth waves, beginning in the late 19th century, was characterized by the widespread adoption of electricity and the internal combustion engine, which transformed industries such as communications, transportation, and manufacturing.

The fourth wave, starting in the early to mid-20th century, saw the rise of information technology, including the development of computers and telecommunications, leading to the digital revolution that reshaped global economies (e.g. personal computer, the internet and mobile communications to significant disruptions and displaced older industries like traditional media, retail, and communication while giving rise to new sectors such as software development, digital platforms, and e-commerce). Currently, we are witnessing the fifth and beginning of the sixth Kondratiev wave, driven by breakthroughs in biotechnology, AI and green technologies. Innovations such as genetic engineering, synthetic biology, and bioinformatics are reshaping sectors ranging from agriculture to materials science, offering cleaner, bio-based alternatives to traditional industries (see Figure 5).





Source: Remesh and Gaba, 2024

The disruptive potential of biotechnology, through innovations like algae-based biofuels, bioplastics, and bio-engineered materials, highlights the ongoing process of creative destruction, where established industries like petrochemicals and fossil fuels are gradually being replaced by more sustainable, bio-based solutions (Sociostudies.org, 2021). Together, Kondratiev's theory of long waves and Schumpeter's concept of creative destruction offer a powerful lens for understanding the ongoing transformations in the global economy. As we move through the current sixth Kondratiev wave, the disruptive impact of biotechnological innovations will not only transform existing industries but also lay the foundation for a more sustainable and resourceefficient future. These theories help explain how technological advancements can both create and destroy industries, ultimately driving economic growth and societal progress. For instance, algaebased biofuels and advanced ethanol production are emerging as viable replacements for conventional gasoline and diesel. Bioplastics like polylactic acid (PLA), derived from renewable resources such as corn or sugarcane, serve as sustainable alternatives to petroleum-based plastics. Moreover, synthetic biology has enabled the creation of bio-engineered materials, including spider silk and bio-based textiles, which offer environmentally friendly substitutes to traditional fibers (sociostudies.org).

These examples align with the concept of the sixth Kondratiev wave of innovation-driven growth, which suggests that new waves of economic growth are driven by disruptive innovations. Biotechnology, as a key driver of the bioeconomy, is a prime example of this disruptive force. The

transition to bio-based economies, fuelled by biotechnological innovations, can be seen as part of this new wave of growth. Biotechnology is poised to disrupt traditional sectors, such as fossil fuels and petrochemicals, by enabling more sustainable alternatives. This disruptive nature of biotechnology is evident in its potential to revolutionize industries ranging from agriculture to energy, contributing to the creation of a new, more sustainable economic paradigm. The figure 6 presents the transition from conventional to Bioeconomy technologies in subsequent sectors.

Sector	Conventional technologies	Bioeconomy technologies
Agriculture	GM Crops: Use of chemical	GM Crops: Genetically modified crops
	pesticides and fertilizers to	like Bt cotton and Roundup Ready
	improve crop yields.	soybeans reduce pesticide use and
		improve yields.
	Traditional Breeding: Slow, less	CRISPR-Cas9 Gene Editing: Precise
	precise crop improvement	modifications to plant genomes for
	methods relying on natural	enhanced nutritional content, disease
	selection.	resistance, and faster growth.
Forestry	Conventional Wood Products:	Bio-based Wood Products: Bio-
	Timber-based products, leading	composites and engineered wood reduce
	to deforestation and	reliance on raw timber, promoting
	overexploitation of forests.	sustainable forestry.
	Traditional Pulp and Paper	Forest Biorefining: Biotechnological
	Production: High resource	processes convert wood into biofuels
	consumption, especially wood	and chemicals, replacing petroleum-
	and water, and significant	derived products.
	environmental impact.	
Fisheries	Aquaculture without Vaccines:	Aquaculture and Fish Vaccines:
	Heavy reliance on antibiotics,	Vaccines improve sustainability by
	contributing to resistance and	reducing antibiotic use and developing
	environmental damage.	faster-growing fish.
	Wild-Caught Fish: Overfishing	Cellular Agriculture for Seafood: Tissue-
	and depletion of fish	engineered seafood minimizes

Figure 6. Comparison of conventional technologies vs bioeconomy technologies

	populations, impacting marine	overfishing and environmental damage,
	ecosystems.	offering a sustainable alternative.
Food	Traditional Meat Production:	Plant-based Proteins: Alternatives like
	High environmental impact,	Beyond Meat provide a sustainable,
	resource-intensive, and	resource-efficient solution to global
	inefficient use of land and water.	protein demand.
	Animal-Derived Ingredients:	Fermentation and Microbial Production:
	Use of dairy, eggs, and other	Genetically engineered microorganisms
	animal products in food	replace animal-derived ingredients with
	production.	plant-based options.
Bioenergy	First-Generation Biofuels: Made	Second-Generation Biofuels: Derived
	from food crops like corn and	from non-food biomass (agricultural
	sugarcane, competing with food	residues, algae, etc.), reducing
	production and using significant	competition with food production.
	land and water.	
	Fossil Fuels: High carbon	Algae-based Biofuels: Algae-based
	emissions, non-renewable, and	biofuels offer higher yield per hectare
	contributes to climate change.	and can be grown on non-arable land,
		reducing competition for land resources.
Bioproducts	Petroleum-based Plastics: Non-	Bioplastics: Biodegradable plastics
	biodegradable, polluting, and	made from renewable sources like corn
	dependent on fossil fuels.	or algae, reducing plastic pollution.
	Petrochemical-based Chemicals:	Bio-based Chemicals: Polyurethanes and
	Derived from fossil fuels,	biodegradable plastics replace fossil
	contributing to environmental	fuel-derived products, reducing
	pollution.	environmental impact.
Wood-Based	Cotton farming involves heavy	Wood-based textile fibers, such as those
Fibers	pesticide use and significant	made from wood pulp (e.g., lyocell,
	water consumption. Synthetic	viscose), are gaining attention as a
	fibers are petroleum-based and	sustainable alternative.
1		

require significant energy and	
chemicals for production.	

Source: own evaluation based on various open access biotechnology solutions.

Studies like those from Shen et al. (2010) and Rüter et al. (2016) demonstrate that using wood to produce textile fibers results in a significant reduction in carbon emissions. The substitution effect of wood-based fibers leads to up to 2.8 kg of carbon saved per kg of carbon produced compared to conventional fibers like cotton and synthetics. This makes wood-based fibers not only more environmentally friendly but also more efficient in terms of overall greenhouse gas (GHG) emissions. Furthermore, wood-based fibers reduce the land-use impact, as their production requires far less land than cotton farming, which is land-intensive and contributes to deforestation. For instance, companies like Lenzing produce lyocell fibers, which are derived from sustainably sourced wood². These fibers require considerably less water and chemicals than traditional cotton farming or synthetic fiber production, making them a more resource-efficient and eco-friendly alternative.

In terms of chemical use and waste, conventional textile technologies, especially in the production of synthetic fibers, involve extensive use of petrochemicals. Additionally, the textile finishing processes often rely on toxic dyes and chemicals, contributing to significant environmental pollution. This not only results in the generation of chemical waste but also leads to wastewater that is frequently discharged into water bodies, further contaminating ecosystems. Moreover, synthetic fibers, due to their petroleum-based nature, contribute to the growing issue of microplastic pollution. In contrast, the production of bio-based fibers, such as lyocell, involves non-toxic chemicals in a closed-loop process, significantly reducing waste and chemical discharge. This process recycles the majority of the solvents used, minimizing environmental pollution.

On the other hand, Manfred Kircher (2025) in his work examining the use of biomass and CO₂ from biogenic sources (e.g., plants, agricultural waste) for sustainable chemical production in the EU. While demand for biomass in energy and chemicals is rising, Kircher highlights the limited supply from agriculture and forestry. He recommends prioritizing edible biomass for food and directing industrial uses toward sectors that need carbon-rich raw materials, like organic chemistry, to avoid competing with food production. The author introduces two key indicators for assessing biomass use in the bioeconomy: value creation intensity (measures how efficiently biomass is used

² The process involves transforming wood (often from sustainably managed forests) into cellulose fibers. Advances are focusing on using mechanical treatments and reducing chemical use (e.g., lyocell uses a non-toxic solvent, and viscose production aims to minimize harmful chemicals).

to create valuable products relative to input, and plant nutrient balance (ensuring that biomass production does not deplete essential soil nutrients, supporting long-term agricultural sustainability). Overall, Kircher emphasizes balancing economic demand with ecological sustainability, using prioritization and efficiency metrics to guide biomass utilization.

These innovations showcase the bioeconomy's potential to provide cleaner, more sustainable alternatives to conventional technologies in many industries. By applying Kircher's proposed indicators—value creation intensity and plant nutrient balance—industries can optimize biomass utilization, ensuring that economic growth does not come at the expense of long-term environmental health. As the bioeconomy continues to evolve, these metrics will be crucial for guiding policy and industrial practices toward a more sustainable and resource-efficient future.

This shift represents a process of creative destruction, where traditional industries and technologies are displaced by more efficient, environmentally responsible alternatives. However, it is crucial that this transition to the Kondratiev sixth wave of innovation is both responsible and balanced. Driven by breakthroughs in biotechnology, the bioeconomy is poised to lead a new phase of growth. As biotechnology fuels the transition to more sustainable practices, it will catalyze long-term economic and environmental benefits, marking a critical point in the evolution of global industrial sectors. This balance will ensure that innovation not only drives progress but does so in a way that fosters sustainability and minimizes disruption to both economic and ecological systems.

In sum, the ongoing sixth wave signifies a pivotal shift in the global economy, with biotechnological innovations poised to reshape industries and promote sustainable growth, as they not only promise new technological breakthroughs but also offer efficient, resource-conserving solutions to address pressing environmental challenges. In *Biomass in the Bioeconomy* (2023), Wertz, Mengal, and Perez argue that the efficient utilization of biomass can significantly reduce dependency on fossil fuels, mitigate climate change, and promote prosperity in rural areas. This dynamic interplay between biotechnology and biomass will boost the next innovation waves, transforming industries and fostering sustainable growth.

The study by Heijman et al (2019) emphasize that the bioeconomy can be a driving force for growth, job creation, and rural development in EU, if significant challenges in scaling up these technologies and ensuring their economic viability are eliminated. Addressing these technological gaps requires substantial investment in further R&D efforts and continued collaboration between all the key stakeholders.

4. From innovation to implementation: the drivers and barriers in scaling the bioeconomy

The transition to a full-scale bioeconomy is influenced by a complex interplay of drivers and barriers. Biotechnology holds immense promise for addressing climate change and fostering sustainability across multiple sectors. The application of bio-solutions, such as biofuels, biodegradable plastics, and carbon capture, has the potential to significantly reduce carbon emissions, improve resource efficiency, and support the transition to a bio-based economy (Smith et al., 2020).

Drivers of the bioeconomy

Technological Advancements in Biotechnology

Biofuels and bioenergy represent one of the major technological advancements driving the bioeconomy forward. The use of biofuels derived from renewable biomass sources can reduce reliance on fossil fuels. In the EU, biofuels accounted for 6.7% of total energy consumption in transport in 2020, with this share expected to grow (Jones & Patel, 2021). Similarly, carbon capture and utilization (CCU) technologies enable the conversion of CO2 into valuable products such as biofuels, chemicals, and construction materials, offering a promising solution for industrial CO2 emissions (Garcia et al., 2019).

The development of biodegradable plastics from renewable resources also helps mitigate the growing issue of plastic waste, as highlighted in the European Commission's European Plastics Strategy (European Commission, 2018). Additionally, the integration of bio-refineries as a central link in new bioeconomy value chains enhances the conversion of biomass into biofuels, power, and chemicals, thereby increasing the sustainability of industrial production (Miller & Brown, 2022).

Advancements in enzyme engineering, synthetic biology, and fermentation processes also drive innovation in the bioeconomy. The ability to engineer microorganisms for the efficient production of bio-based chemicals, pharmaceuticals, and materials accelerates the shift towards a sustainable bioeconomy. The role of computational tools, AI, and big data in optimizing biotechnology applications further enhances the efficiency and scalability of bioeconomic solutions (Zhang & Li, 2020).

Regional and Global Policy Support

Policy initiatives at the EU and regional levels play a crucial role in advancing the bioeconomy. The European Green Deal and Horizon Europe provide significant funding for research and development in biotechnology and biomanufacturing. The EU Bioeconomy Strategy and EU Cohesion Policy support regional bioeconomy initiatives, while the European Regional Development Fund facilitates piloting and implementing bio-based industries at the regional level (Johnson et al., 2023).

In Denmark, the government has recognized biotechnology as a key economic and sustainability driver, making substantial investments in biotechnology and biomanufacturing (Andersen & Nielsen, 2021). Furthermore, globalization influences the bioeconomy by harmonizing value chains and consumer attitudes, enabling international trade and investment in bio-based products (Gonzalez & Perez, 2022).

Environmental and Market Incentives

The increasing importance of climate change and pressure on ecosystems serve as a major driver for the bioeconomy. Climate change is a significant challenge for the agricultural and forestry sectors, but the bioeconomy can help mitigate its effects by reducing emissions and fostering sustainable land management practices (Thompson et al., 2019). Bio-based products, such as biofuels and bio-materials, typically have lower CO2 footprints than their fossil-based counterparts. Additionally, resource availability, including biomass from agriculture, marine ecosystems, and forestry, is crucial for the expansion of bio-based industries (Rodriguez & Kim, 2021).

Market demand for sustainable and eco-friendly products continues to rise, encouraging industries to adopt bio-based solutions. Consumers and businesses are increasingly considering environmental impact when making purchasing decisions, reinforcing the economic viability of bio-based products (Lee et al., 2020).

Barriers to the bioeconomy

Regulatory and Legislative Challenges

Despite strong policy support, the bioeconomy faces significant regulatory hurdles. Complex regulatory frameworks, particularly regarding genetically modified organisms (GMOs), can delay product approval and commercialization (Fischer & Schmidt, 2018). The absence of specific EU bioeconomy legislation adds to the complexity, with various policies, such as the Renewable Energy Directive and Waste Framework Directive, influencing the sector's development (European Commission, 2020).

The fragmented regulatory landscape across different regions creates inconsistencies in compliance requirements, slowing down cross-border collaborations and the scalability of bio-based solutions. The slow adaptation of regulations to emerging biotechnologies further complicates their implementation in commercial applications (Kumar & Banerjee, 2019).

Economic Constraints

High development costs present another major barrier. Biotech research and development require substantial investments, particularly in the early stages, which can be burdensome for small and medium-sized enterprises (SMEs) (Williams & Green, 2022). Moreover, access to financing remains a challenge, despite EU funding opportunities such as Horizon Europe and the European Agricultural Fund for Rural Development (EAFRD) (European Commission, 2021).

The initial costs of bio-based solutions often remain higher than those of traditional fossil-based products, discouraging widespread industry adoption. Additionally, the long commercialization timeline for biotech innovations can deter private investors from funding bioeconomy ventures (Cheng et al., 2022).

Infrastructure and Expertise Gaps

The lack of specialized infrastructure and skilled workers limits the ability to scale up biotechnological innovations. Many European regions have expressed ambitions to establish biobased industries, yet only a few, such as Hauts-de-France and Grand Est in France, Biobased Delta in the Netherlands, and Central Finland, have successfully developed bioeconomy clusters (Larsen & Petersen, 2020). The presence of established chemical, energy, and pulp industries in these regions provided a strong foundation for attracting investment and fostering innovation.

A shortage of interdisciplinary expertise in biotechnology, environmental science, and business development further impedes the growth of the bioeconomy. Educational programs and vocational training focused on bioeconomy-related skills must be strengthened to address this gap (Davis et al., 2021).

Public Perception and Market Acceptance

Public resistance to biotechnological solutions, particularly in agriculture and food production, remains a significant challenge. Concerns over genetically modified crops, bio-based plastics, and synthetic biology-based products hinder consumer acceptance and market growth (Hansen & Clark, 2019). Additionally, bio-based products may have higher water, eutrophication, and land-

use footprints than fossil-based alternatives, raising concerns about their overall sustainability (Wilson et al., 2021).

Misinformation and a lack of awareness about the benefits and risks of bio-based innovations contribute to scepticism among consumers and policymakers. Effective communication strategies and public engagement efforts are essential to build trust and promote the adoption of bioeconomy solutions (Parker et al., 2022).

In sum, the implementation of a full-scale bioeconomy presents both opportunities and challenges. The process of creative destruction within the biotechnology sector has the potential to reshape industries, reduce environmental impacts, and create sustainable solutions. However, economic costs, regulatory complexities, and technological scaling remain significant barriers (Schneider et al., 2023).

With supportive policies, continued innovation, and international collaboration, biotechnologydriven solutions can replace conventional technologies and pave the way for a more sustainable future. Addressing regulatory challenges, fostering investment in biomanufacturing infrastructure, and enhancing public awareness will be crucial in overcoming barriers and ensuring the successful expansion of the bioeconomy.

5. The rise of bioeconomy - the case of the EU vs. the US

The European Union

Europe is undergoing a transformative shift toward a sustainable, net-zero economy, with biotechnology playing a pivotal role in this creative disruption process. The bioenergy sector exemplifies how innovation in biotechnology is reshaping Europe's energy landscape, reducing carbon emissions, and fostering economic growth. The 2024 Bioenergy Europe Landscape Report provides compelling evidence that bioenergy is not only a key driver of decarbonization but also a crucial component of Europe's energy independence and industrial competitiveness. Bioenergy currently constitutes 54% of the EU's renewable energy mix, underscoring its dominant role in Europe's clean energy landscape. In 2022 alone, it contributed to avoiding 300 million tonnes of CO₂ emissions annually, marking a significant step toward the EU's reliance on external energy imports by leveraging locally sourced biomass, thereby strengthening regional energy security and resilience.

The sector's economic impact is equally substantial. As of 2023, the bioenergy industry supports 1.5 million jobs across Europe and is projected to contribute up to \notin 70 billion to EU GDP by 2050, particularly benefiting rural communities where bioenergy investments drive employment and sustainable development. This progress is fueled by biotechnology-driven innovations in bio-based carbon removal, biofuel production, and biomass optimization. Technologies such as Bioenergy with Carbon Capture and Storage (BECCS) exemplify Europe's commitment to carbon-negative solutions. BECCS not only captures and stores CO₂ emissions but also enables the production of carbon-neutral energy, positioning bioenergy as a crucial tool in achieving the EU's net-zero targets.

The momentum of renewable energy growth further reinforces this shift, with the share of renewable energy in the EU's final energy consumption reaching 23% in 2022, of which bioenergy contributed more than half. Since 2015, the EU has invested over €30 billion in bioenergy research and development, increasingly focusing on advanced biofuels and bio-based materials. With an ambitious goal to reduce greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels, bioenergy is expected to play a key role in meeting these targets. Additionally, the EU has significantly improved its energy security by reducing its energy dependency ratio to 58% through the replacement of fossil fuel imports with locally produced bioenergy.

To maximize bioenergy's potential and accelerate Europe's transition to a net-zero economy, policymakers must address both the drivers and barriers to sectoral growth. Strong policy support through initiatives like the Green Deal and the Bioeconomy Strategy has incentivized bio-based product development, reinforcing Europe's leadership in sustainable energy. However, challenges remain, including high production costs, regulatory hurdles, and a lack of consumer awareness and infrastructure. Expanding funding and regulatory support for BECCS and other bio-based carbon removal solutions is essential, alongside establishing market mechanisms that reward negative emissions to ensure the economic viability of these technologies. Modernizing heating systems through incentive programs for high-efficiency bioheat technologies and mandating sustainable biomass use in district heating and industrial applications will further reduce fossil fuel dependence.

Ensuring a sustainable biomass supply chain is also critical. Developing a harmonized EU-wide certification system will guarantee responsible biomass sourcing while enhancing forest and agricultural residue utilization without compromising biodiversity and ecosystem protection. Finally, providing regulatory stability is key to encouraging long-term investment in bioenergy.

Establishing clear regulatory frameworks and aligning EU bioeconomy strategies with industrial policies will foster synergies between bioenergy, biotechnology, and circular economy initiatives.

The 2024 Bioenergy Europe Landscape Report highlights the transformative role of bioenergy in Europe's decarbonization journey. By fostering biotechnology-driven innovation, ensuring a sustainable biomass supply, and providing a stable regulatory environment, the EU can unlock bioenergy's full potential. As Europe continues to lead the global transition to a sustainable economy, bioenergy remains a cornerstone of its strategy, demonstrating the power of biotechnology-driven creative disruption in shaping a cleaner, more resilient future.

The book further highlights the EU's role in maintaining its global competitiveness within the bioeconomy, which requires strategic investments and policy initiatives to position Europe as a leader in bio-based industries. In this context, the disruptive innovations in biotechnology are not only central to fostering economic development but also to securing Europe's competitive advantage on the global stage. By addressing technological, policy, and environmental challenges, Europe can harness the full potential of the bioeconomy, paving the way for sustainable growth and positioning itself at the forefront of the sixth Kondratiev wave of innovation.

The United States

The bioeconomy represents an essential and growing sector within the United States, integrating biotechnology, engineering, and computational sciences to foster economic growth. However, the absence of an officially accepted definition complicates its analysis and decision-making processes. The U.S. bioeconomy is characterized by an emphasis on biotechnology, biomedical advancements, and national security applications. However, the country faces both drivers as well as significant barriers to the full-scale adoption of the bioeconomy, throughout its historical trajectory, policy frameworks, and existing cost-efficiency challenges. The bioeconomy represents an essential and growing sector in the US, integrating biotechnology, engineering, and computational sciences to foster economic development. However, its analysis and decision-making processes are complicated by the absence of an officially accepted definition. The U.S. bioeconomy, with its focus on biotechnology, biomedical advancements, and national security applications, has seen significant growth in the past decades, yet also faced distinct challenges in fully realizing its potential.

One of the key drivers of the U.S. bioeconomy is its strong emphasis on innovation and research in biotechnology. According to the National Academies of Sciences, Engineering, and Medicine (NASEM), the bioeconomy accounted for over 5% of the U.S. GDP, approximately \$959.2 billion, in 2016. The focus on biotechnology, genetic engineering, and synthetic biology

fuels innovation and supports advancements in agricultural, biomedical, and bio industrial fields. Government initiatives also play a crucial role in advancing the bioeconomy. The Obama Administration's National Bioeconomy Blueprint (2012) set strategic objectives aimed at fostering research and development (R&D), regulatory reforms, workforce training, and public-private partnerships. More recent policies, such as the CHIPS and Science Act (2022) and the Executive Order on Advancing Biotechnology and Biomanufacturing (2022), continue to reinforce the U.S. commitment to bioeconomic growth, although the strategies remain fragmented across federal agencies. Public-private collaborations are another significant driver of the bioeconomy. Key entities such as the U.S. Department of Agriculture (USDA), the Department of Energy (DOE), and the Biomass R&D Board have spearheaded initiatives to expand biomass production, biofuels, and bio-based products. The DOE's 2016 Billion-Ton Bioeconomy report modelled biomass resource availability and sustainability, while partnerships between universities, research institutions, and industry leaders continue to push bioeconomic advancements. Additionally, economic and environmental incentives have fuelled the growth of bio-based industries. The shift toward bio-based production helps reduce dependence on fossil fuels, lowers carbon footprints, and improves agricultural efficiencies. With the passage of the Inflation Reduction Act (2022), investments in bio-based industries are further incentivized, particularly those focused on clean energy and sustainable manufacturing.

However, several barriers impede the full-scale adoption of the bioeconomy in the US. One of the most significant challenges is the lack of a unified definition and clear long-term strategy. Unlike the EU, which includes primary sectors like agriculture, fisheries, and forestry in its bioeconomy framework, the US focuses on more limited aspects, such as genetically modified crops. This lack of a clear, cohesive definition hinders policy coordination and measurement, making it difficult to achieve a unified approach to bioeconomic development. A national strategy, similar to the EU's Bioeconomy Strategy (2018), could help streamline efforts and foster growth in a more structured manner.

Regulatory and infrastructure challenges also pose significant barriers. The slow pace of regulatory reforms, high costs of compliance, and policy uncertainty create obstacles for industry stakeholders. Infrastructure limitations, supply chain inefficiencies, and the need for improved logistics in biomass distribution, as identified in the 2016 Biomass R&D Board report, further complicate the adoption of bioeconomy solutions. The fragmentation of jurisdiction over bioeconomy-related sectors, with different agencies such as the FDA, USDA, and EPA overseeing various aspects, exacerbates regulatory bottlenecks.

Workforce development and talent retention are additional hurdles. The 2019 White House Bioeconomy Summit highlighted the need for skilled professionals and greater alignment between academic training and industry demands. Addressing workforce shortages is critical to maintaining innovation and competitiveness in the bioeconomy. Investments in STEM education, vocational training, and stronger industry-academic partnerships are needed to cultivate a workforce capable of addressing future bioeconomic challenges.

Finally, public perception and market readiness remain significant barriers. Consumer acceptance of bio-based products, particularly in food and pharmaceutical applications, continues to be a challenge. Educational campaigns are needed to raise awareness about the benefits of bioeconomy innovations. Ethical concerns surrounding synthetic biology and genetic modification further complicate public acceptance and regulatory approval processes.

In the context of recent political shifts, the second Trump administration has brought a wave of new policies that have impacted the bioeconomy. His policies, including executive orders aimed at cutting red tape and promoting private sector growth, while do not impact biotechnology sectors, the administration's approach raises concerns about potential rollbacks of environmental protections and regulatory oversight, which could slow progress in certain bioeconomy areas. Despite these concerns, the continued emphasis on deregulation and market-driven solutions in the US presents opportunities for bioeconomy innovation. Though it will require careful balancing with long-term sustainability goals. The trajectory of the bioeconomy under these new policies will likely depend on how well stakeholders in both the public and private sectors can navigate the complex regulatory landscape and align their efforts toward advancing both economic growth and environmental sustainability.

In summary, a comparative analysis of the bioeconomy in the EU and the US reveals distinct drivers and barriers in each region, shaped by their unique policy frameworks and economic contexts. In the EU, the primary drivers of bioeconomy development are robust policy initiatives, such as the Green Deal and the Bioeconomy Strategy, which provide strong incentives for the growth of bio-based products. However, significant barriers exist, including high production costs, complex regulatory environments, and insufficient consumer awareness, alongside a lack of infrastructure necessary for the large-scale adoption of bio-based alternatives. Conversely, the drivers in the US are predominantly fuelled by substantial investments in bioenergy technologies and the country's extensive agricultural capacity, which together foster the expansion of bioeconomy initiatives. Nevertheless, barriers in the US include rising policy uncertainty, as well as competition from established fossil fuel industries, which impede the long-term sustainability and scalability of bio-based industries.

The comparative challenges in both regions highlight the divergent structural and policy landscapes that influence the development of the bioeconomy, ultimately shaping the trajectory of bio-based industries in the EU and the US. These differences underscore the varying pace and scale of bioeconomy growth globally.

6. Conclusion and policy implications

To successfully launch the sixth Kondratiev innovation wave, driven by bioeconomy, both global and national policymakers must adopt a multi-faceted approach that aligns innovation with sustainability, economic growth, and the challenges posed by climate change. As biotechnology transforms industries, particularly in the realms of bioenergy, biofuels, and sustainable products, the policy implications for fostering this new wave of innovation are critical. Bioeconomy has the potential to reshape economies, reduce dependency on fossil fuels, and bolster rural development, but it will require robust and strategic policy frameworks to overcome the barriers to its widespread adoption.

The EU exemplifies the transformative potential of bioeconomy, with its focus on advancing biotechnology through initiatives like the Green Deal and the Bioeconomy Strategy. These initiatives emphasize reducing carbon emissions, enhancing energy security, and promoting economic development through bio-based industries. By incentivizing bioenergy innovations such as Bioenergy with Carbon Capture and Storage (BECCS), the EU is positioning itself at the forefront of the bioeconomy revolution. However, several challenges remain, including high production costs, regulatory complexities, and the need for infrastructure development. Policymakers must expand funding for research and development in bioenergy technologies, particularly those that focus on carbon-negative solutions. Additionally, creating a harmonized certification system for biomass sourcing will ensure sustainability while promoting economic opportunities, particularly in rural areas. The EU should also invest in modernizing energy systems and establishing market mechanisms that reward negative emissions, thereby making bio-based technologies economically viable in the long term.

On the global stage, the US plays a crucial role in advancing bioeconomy, particularly through its strong emphasis on biotechnology, biomedical advancements, and national security applications. The US bioeconomy, fuelled by substantial investments in bioenergy and bio-based production,

faces unique challenges, such as the lack of a unified national bioeconomy strategy. Unlike the EU, the US has yet to adopt a comprehensive framework that integrates all sectors of its bioeconomy, ranging from agriculture to forestry and bioenergy. To address this, the US should develop a coherent national bioeconomy strategy that aligns the efforts of various stakeholders, including government agencies, academic institutions, and private companies. In particular, the federal government should expand initiatives that promote public-private partnerships, as these collaborations are crucial for driving innovation and addressing regulatory hurdles. Additionally, policymakers should streamline regulatory processes to reduce compliance costs and facilitate the large-scale deployment of bioeconomy solutions. Investments in workforce development are also essential, as a skilled workforce is needed to support the continued growth of the bioeconomy. Strengthening STEM education and vocational training in bioeconomy-related fields will be crucial for maintaining the United States' competitive advantage in this sector.

Both the EU and the US must navigate several critical issues to realize the full potential of bioeconomy. Environmental sustainability must remain a central consideration, ensuring that biobased solutions do not inadvertently harm ecosystems or biodiversity. Policymakers need to carefully balance economic growth with sustainability goals, particularly when it comes to biomass utilization, which can have negative environmental impacts if not properly managed. Regulations should encourage innovation while simultaneously safeguarding the environment, ensuring that the bioeconomy does not exacerbate issues such as deforestation or over-exploitation of natural resources.

At the global level, international cooperation will be crucial in addressing the systemic challenges of scaling up bioeconomy. The UN's Sustainable Development Goals (SDGs) provide a framework for aligning bioeconomy growth with broader sustainability objectives, including climate change mitigation, poverty reduction, and food security. Countries must work together to share best practices, harmonize standards, and address global supply chain challenges. International policy frameworks that encourage bio-based innovations, such as sustainable biofuels and biodegradable plastics, could stimulate both market demand and cross-border collaborations, accelerating the global transition to a bio-based economy.

In conclusion, the successful launch of the sixth Kondratiev wave, powered by bioeconomy, hinges on policymakers' ability to foster an environment conducive to innovation, collaboration, and sustainable development. Immediate steps must include the development of concrete regulatory frameworks, tailored financial incentives, and the establishment of public-private partnerships. By addressing technological, regulatory, and economic barriers, and ensuring a focus on sustainability, both the EU and the US can lead the way in advancing bioeconomy. Additionally, integrating social equity considerations and ensuring that bioeconomy policies benefit all sectors of society will be critical for long-term success.

In conclusion, the successful transition to a bioeconomy hinges on the effective combination of public policy support, private sector innovation, and international collaboration. With these elements in place, the bioeconomy has the potential to drive global economic growth while addressing some of the most pressing challenges of our time, including climate change, resource depletion, and economic inequality. However, this transformation requires urgent action and collaboration across all levels of society to realize its full potential. While the transition to a bioeconomy may take several decades, significant milestones are likely to be reached by the 2040s, with gradual adoption beginning in sectors such as bioenergy, sustainable agriculture, and bioplastics in the coming years. The pace of this transition will vary by region, influenced by technological readiness, policy support, and market conditions. Ultimately, achieving a sustainable and equitable bioeconomy will depend on continuous innovation, strategic investments, and global cooperation.

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