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# The third wave of biomaterials: When innovation meets demand

How corporate sustainability commitments could catalyze the next generation of bio-based chemicals and materials.

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**Biomaterials have long been** a part of our daily lives, from wooden houses to woolen clothes. More recently, biotech advances have brought us sugar-derived first-generation biofuels and high-performance enzymes to power our laundry detergents. Now, we see the emergence of nylon made using genetically engineered microbes instead of petrochemicals, alternative leather from mushroom roots, and cement from bacteria.

These advances in biological science are bolstered by accelerating innovations in computing, automation, and artificial intelligence (AI), resulting in a new wave of innovation known as the Bio Revolution. McKinsey Global Institute research has found that as much as 60 percent of the physical inputs to the global economy today are either biological (wood or animals bred for food) or nonbiological (cement or plastics) but could in principle be produced or substituted using biological means. Over the next ten to 20 years, advances in the use of biology in the production of materials, chemicals, and energy could amount to $200 billion to $300 billion in global market growth.[1]

What will drive this growth? Historically, adoption of bio-based materials has been the result of a unique technical or cost advantage, the latter of which is difficult to gain against highly developed and large-scale incumbent technologies. But this equation is changing because of accelerating corporate commitments to sustainability and the ability of biomaterials to help companies meet their targets. As biological innovation meets downstream demand, a new wave of the Bio Revolution in chemicals and materials is unfolding—with enormous potential impact.

## The three waves of innovation in biomaterials

The first wave of biomaterials spanned the millennia before the age of petroleum. Bio-based materials from plants or animals became a fixture of society and still surround us today in the form of wood, paper, leather, textiles, and numerous other derivatives that are used for adhesives, soaps, pigments, and other substances.

The second wave was catalyzed by the birth of biotech and recombinant DNA technology in the 1980s. These developments gave rise to companies like California-based Genencor and the modern industrial enzyme industry, which has led to dramatic improvements in products ranging from laundry detergent to animal feed.

This second wave reached its zenith when further advances in biotechnology collided with high prices for fossil-based chemical feedstock (oil, gas) and dot-com-era excitement in the mid-2000s, driving a boom in cleantech and biotech investments focused on commodity biofuels and biomaterials. Yet high fossil-based feedstock prices proved fleeting while rising prices on the biomaterials side and high volatility for renewable feedstocks such as corn and sugar through the 2000s further diminished any potential cost advantage. With the subsequent rise of fracking and electric vehicles, sustained fossil-based feedstock prices—more than $100/barrel for oil, for example—looked increasingly unrealistic.

As cost superiority to petrochemical production routes became a less attractive investment, many companies in the biomaterials sector went back to the drawing board and pivoted to specialty applications for which bio-based production could yield unique chemistries. Although the second wave ended with some disappointment, it taught critical lessons in techno-economic discipline while illustrating the enormous potential of biotechnology.

Today, the Bio Revolution continues to play out its third wave, with rapid advances each year in DNA sequencing, gene editing, AI, and other technologies that ultimately benefit the development of biomaterials. However, what is truly different this time around is that sustainability is changing the basis of competition in chemicals and materials and is creating demand-side disruption.

[1] For more, see Michael Chui, Matthias Evers, James Manyika, Travers Nisbet, and Alice Zheng, “The Bio Revolution: Innovations transforming economies, societies, and our lives,” McKinsey Global Institute, May 13, 2020, on McKinsey.com.

# As biological innovation meets downstream demand, a new wave of the Bio Revolution in chemicals and materials is unfolding—with enormous potential impact.

One takeaway from the second wave of biomaterials was that "green premiums," or the ability to charge a higher price for a green technology, were unreliable: if they existed at all, they were modest at best and largely confined to market niches. However, recent pushes from three different groups—consumers, regulators, and investors—have led to significant actions from corporations, suggesting that there may indeed be, if not a clear and bankable "green premium," then a sizable and fast-growing market for sustainable chemicals and materials.

Regarding the first group, consumer demand for greener products is rising. A recent McKinsey survey of ten countries found that consumers see sustainability as increasingly important, and the vast majority of consumers say they are willing to pay more for sustainable packaging across a diverse set of countries—for example, in China (86 percent of consumers are willing to pay "a lot" or "a bit" more for sustainable packaging), the United States (68 percent), and Brazil (66 percent).[2]

Meanwhile, regulators are pushing for sustainability through initiatives such as the European Green Deal. Two key regulatory objectives are reducing $CO_2$ emissions and environmental leakage of plastics that do not biodegrade. Both can be addressed through biomaterials.

Finally, with mounting assets under management in environmental, social, and governance (ESG) funds, investors are increasing pressure on corporations to reduce their transition risk through decarbonization and to ensure they are positioned to capitalize on growth opportunities necessary to decarbonize the rest of the economy.

In response to the pushes from these three groups, as well as from their own employees, many corporations are committing to reducing their environmental impacts. For example, a majority of top automakers and the leading fast-moving consumer-goods players have committed to substantial reductions in greenhouse-gas (GHG) emissions. These targets—and their impact on purchasing and manufacturing decisions—are changing the game for products with a sustainability value proposition.

## Corporate climate commitments are accelerating rapidly

Companies are making many types of sustainability commitments. Many commitments are relevant for chemical and material companies, such as total material reductions (the reduction of packaging materials), content sourcing (using recycled or renewable bio-based materials), and end-of-life fate (whether materials wind up as recyclable, compostable, or biodegradable).

However, the most broadly consequential commitments relate to GHG-footprint reductions. We examined five end markets for chemicals and materials and found that a vast majority of leading companies (74 percent) have already made commitments concerning Scopes 1 and

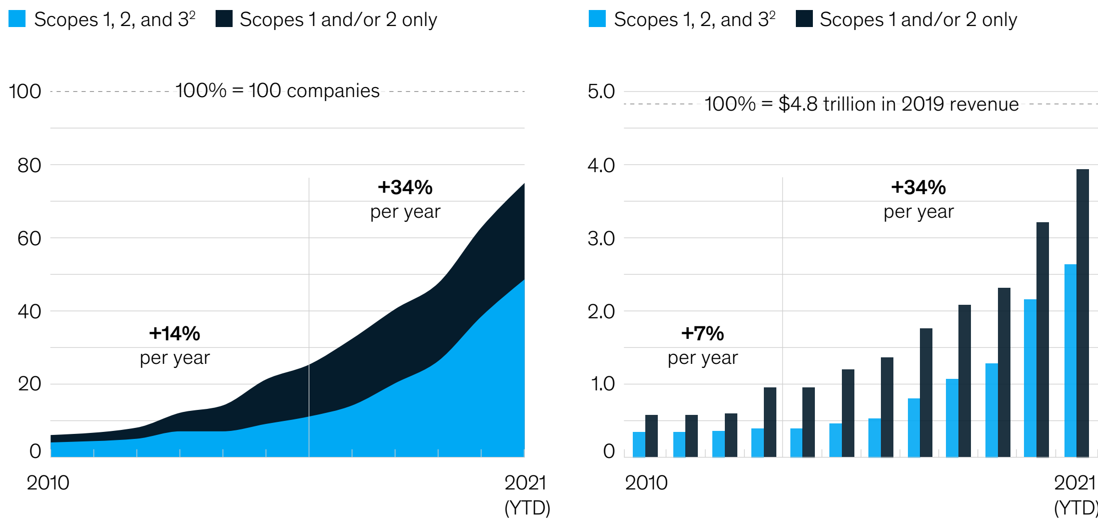
[2] Daniel Eriksson, David Feber, Anna Granskog, Oskar Lingqvist, and Daniel Nordigården, "Sustainability in packaging: Inside the minds of global consumers," December 16, 2020, McKinsey.com.

Exhibit 1

## Commitments to reduce Scope 3 greenhouse-gas emissions are accelerating.

**Companies with emissions-reduction commitments,** number of top companies across end markets[1]

**Cumulative 2019 revenue with associated commitments,** $ trillions across end markets[3]




[1]Top 20 companies by 2019 global revenue in each of five end markets: apparel, automotive, electronics, fast-moving consumer goods (food, home, and personal care), and packaging.
[2]Scope 1 covers direct emissions from owned or controlled sources, including emissions from the combustion of fuel and vehicles. Scope 2 covers indirect emissions from the generation of purchased electricity, steam, heating, and cooling. Scope 3 emissions are not directly owned by the company but cover all other indirect emissions that occur in a company's value chain.
[3]Sum of 2019 revenue associated with top 20 companies across end markets.

Source: Environmental, Social, and Governance (ESG) by McKinsey; Sustainability Insights by McKinsey; McKinsey analysis

2 emissions. Nearly 50 percent have committed to Scope 3 GHG emissions reductions (see sidebar, "What are Scope 3 emissions?"), including the emissions associated with the upstream production of ingredients and raw materials.

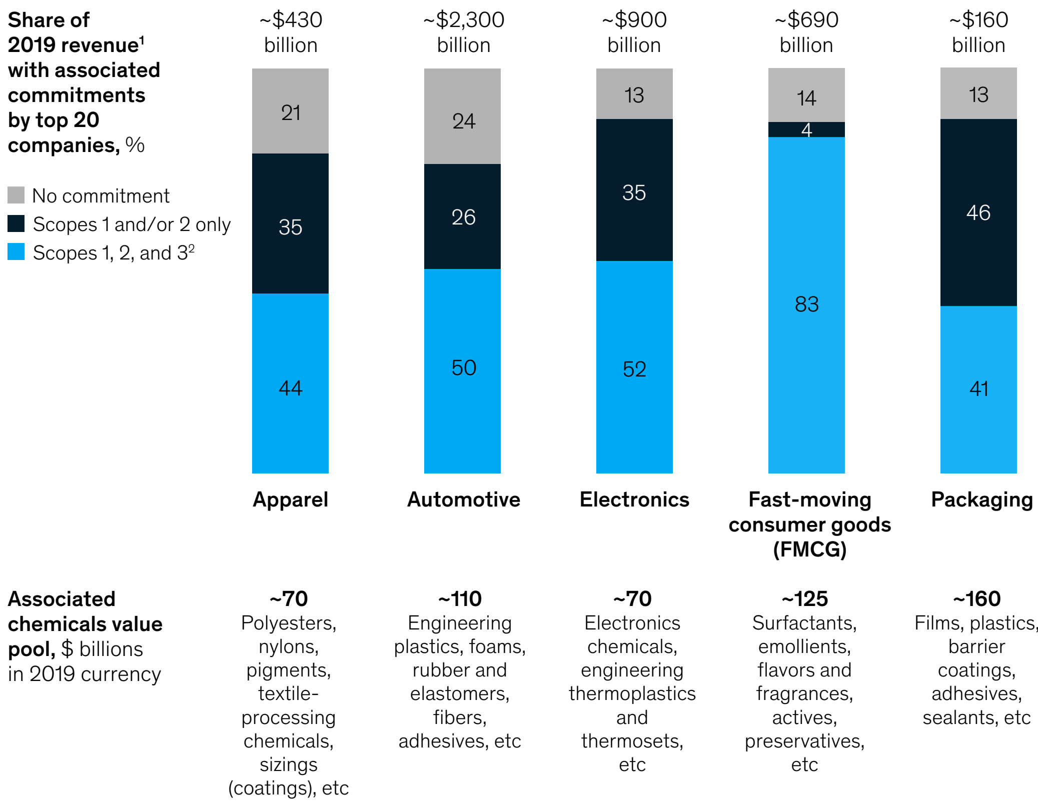
A majority of Scope 3 commitments are scheduled to be fulfilled by 2030. There is also an overall trend toward committing to net-zero emissions by 2040 to 2050—and this trend is accelerating (Exhibit 1). In fact, the number of companies committed to Scope 3 reductions increased by a CAGR of 34 percent from 2016 to 2021, a significant increase from the 14 percent average from 2006 to 2015. The share of revenue associated with Scope 3 commitments has also grown to $2.6 trillion in 2021, up from $0.5 trillion in 2016.

Consider the impact of increased Scope 3 commitments on the chemicals and materials industry: half a trillion dollars in spending is now under scrutiny. Take the automotive industry. Since 2019, 50 percent of the end-market revenues of the top 20 automotive OEMs have been linked to Scope 3 emissions–reduction commitments (Exhibit 2). This means the use of chemicals such as elastomers, fibers, thermoplastics, and foams, which represent about $110 billion in revenue for the chemical sector, will come under scrutiny.

Commitments to reduce Scope 3 emissions appear similar across end markets at about 30 to 35 percent but vary significantly among companies (around 30 percent median reduction, with an approximate range of 20 to 100 percent). Among the top 20 companies across several sectors, the lowest number of companies making such commitments was only six in packaging, whereas the highest number was 16 in fast-moving consumer goods (FMCG). Apparel, electronics (eight each),

Exhibit 2

## Approximately $500 billion of spending on chemicals and materials is under scrutiny.




Note: Figures may not sum to 100%, because of rounding.
[1]Sum of 2019 revenue generated by top 20 companies in each end market: apparel, automotive, electronics, fast-moving consumer goods (top 20 companies across food, home, and personal care sectors), and packaging.
[2]Scope 1 covers direct emissions from owned or controlled sources, including emissions from the combustion of fuel and vehicles. Scope 2 covers indirect emissions from the generation of purchased electricity, steam, heating, and cooling. Scope 3 emissions are not directly owned by the company but cover all other indirect emissions that occur in a company's value chain.
Source: Environmental, Social, and Governance (ESG) by McKinsey; Sustainability Insights by McKinsey; McKinsey analysis

and automotive (nine) are all nearing the 50 percent mark for the portion of top 20 players with Scope 3 commitments.

The relatively high reading for FMCG may reflect the fact that consumer-facing companies are more aware of, and therefore more sensitive to, pressure from customers for sustainable options. Many acknowledge that consumers have given them a "social license to operate" and that committing to cutting emissions is an opportunity to lead their respective markets and differentiate themselves from their competitors.

## Bringing biomaterials to market

Biomaterials are among multiple levers that companies can pull to improve the sustainability of their supply chains and products. The question is how biomaterial producers can chart a clear role for their products amid other options, such as greener manufacturing and recycling. Understanding the nuances around creating value from sustainability is the first step, followed by determining the best possible use cases across the three types of biomaterials.

## What are Scope 3 emissions?

**Greenhouse-gas (GHG) emissions** are categorized into three groups, or “scopes,” by the Greenhouse Gas Protocol,[1] the most widely used international accounting tool for emissions.

Scope 1 covers direct emissions from owned or controlled sources, including emissions from the combustion of fuel and vehicles. Scope 2 covers indirect emissions from the generation of purchased electricity, steam, heating, and cooling. Scope 3 emissions are not directly owned by the company but cover all other indirect emissions that occur in a company’s value chain. This includes both upstream emissions (goods-and-services purchases, transportation and distribution, business travel, commuting by employees, and waste generated in operations) and downstream emissions (the use of products sold, end-of-life treatment of products sold, transportation and distribution, investments, leased assets, and franchises). Scope 3 emissions are also referred to as the GHG Protocol Corporate Value Chain,[2] as the protocol takes a value-chain or life-cycle approach to GHG emissions.

The Corporate Value Chain (Scope 3) Standard helps companies identify GHG-reduction opportunities, track performance, and engage suppliers at a corporate level, while the Product Standard helps companies meet the same objectives at a product level. Together with the GHG Protocol Corporate Standard, the three standards provide a comprehensive approach to value-chain GHG measurement and management.

Most of the largest companies in the world now account for and report on the emissions from their direct operations—Scopes 1 and 2—and the standards set in the protocol are aimed at covering Scope 3. Developing a full GHG-emissions inventory enables companies to understand their full value-chain emissions and to focus their efforts on the greatest GHG-reduction opportunities in collaboration with suppliers and customers.

[1] “FAQ,” Greenhouse Gas Protocol, ghgprotocol.org.
[2] “GHG Protocol Corporate Value Chain (Scope 3) and product life cycle standards,” Greenhouse Gas Protocol, ghgprotocol.org.

**A potential sustainability solution**

Although biomaterials are better poised than ever to offer sustainability benefits, including reduced carbon footprints, improved biodegradability or recyclability of materials, and superior performance in certain applications, there are several considerations critical to ensuring that biomaterials actually deliver a net-positive sustainability impact.

For example, the sustainability profile of biomaterials can vary depending on the feedstock selection (for example, corn versus refined sugars and the use of waste products in lieu of edible starches to produce second-generation [2G] fuels), farming practices (for example, regenerative agriculture to increase soil carbon content, fertilizer application rates and management, and overall yield and productivity), and land-use policies (for example, avoiding deforestation to increase production of tropical feedstocks such as palm). That said, with appropriate considerations and precautions in place, biomaterial producers can minimize counterproductive side effects en route to meeting the needs of customers, regulators, investors, and consumers alike.

**Biomaterial product types**

Not all biomaterials are created equally. Beyond simply reducing cost and environmental impact, biomaterial companies must understand the technical differentiation of their products and the value chains in which they are looking to sell. The relative importance of these factors varies across three biomaterial product types, with potential use cases for different end markets (Exhibit 3).

1. *Drop-ins:* This bio-based production route is used to make a product traditionally derived from petrochemicals—for example, Braskem’s bioethanol-based polyethylene. “Drop-ins” refer to chemicals that can essentially be dropped into existing products without changing surrounding

operations. For bio-based drop-in chemicals, life-cycle carbon-emissions reductions of 50 percent (or more) are possible relative to traditional petrochemical routes, but this will vary based on the specifics of the bio-based and petrochemical routes. This represents a significant value proposition for companies looking to reduce their Scope 3 footprints. Companies that succeed with drop-ins can develop efficient, cost-competitive (although not necessarily lower-cost) processes and identify the specific customer segments that are interested in greener materials.

2. *Bio-replacements:* For this product type, a bio-based chemical is used to make a new material that is effectively at parity for measures such as technical performance and cost but that offers a significant improvement in environmental impact—for example, novel fermentation-derived surfactants used in detergents. These are perhaps the most difficult products to succeed with because they can require complex changes across the value chain without delivering technical differentiation. Success requires sharply targeting applications that have low regulatory and testing barriers to incorporate new materials and build a strong consumer-facing element. This way, beneficial environmental impact is optimized.

3. *Bio-better:* Unique biochemical synthesis routes can enable completely new combinations of material properties, such as biotech-derived optical films. In this case, the technical advantages are the primary driver of product adoption, with the added bonus of enhancing the environmental profile. The traditional

[3] Michael Boren, Vanessa Chan, and Christopher Musso, "The path to improved returns in materials commercialization," August 1, 2012, McKinsey.com.

Exhibit 3

## Three biomaterial product types can help companies choose the best end markets.

**Selected examples**

| | Drop-ins | Bio-replacements | Bio-better |
|---|---|---|---|
| **Apparel** | Existing materials such as nylon and spandex created through bio-routes | Sustainability-oriented clothing created using biomass waste streams | Biotech versions of first-wave biomaterials, such as leather and silk, for improved performance and sustainability profiles |
| **Automotive** | Bio-based intermediates in thermoplastics production,[1] such as polybutylene terephthalate (PBT) | Plant-based fibers, such as kenaf, to replace glass fibers | Biotech products with superior heat conduction necessary during fast charging for electric vehicles |
| **Electronics** | Bio-based intermediates for the production of petrochemically derived plastics used in housing and other structures | New polymers that have properties near those of established petrochemically derived plastics, such as ABS[2] | New products for displays using unique biotech material properties, with potential for milder chemistries |
| **Fast-moving consumer goods (FMCG)** | Replacement of petrochemicals or extracted flavors and fragrances with biotech to drive scalable or more natural products, such as vanilla | Replacement of petrochemical- or, increasingly, palm oil–derived surfactants (potentially at performance parity) | New cosmetic active ingredients discovered through metagenomic approaches |
| **Packaging** | Bio-based versions of widely used materials, such as polyethylene | "Bio-only" materials such as PLA[3] and increased use of first-wave biomaterials such as starches | Novel biotech films that combine barrier properties (eg, to protect food content) with recyclability (unlike today's solutions, often hard-to-recycle material mixes) |

[1] Chemicals that are persistent, bioaccumulative, and toxic to the environment.
[2] Acrylonitrile butadiene styrene, often used in appliance housing and automotive interiors.
[3] Polylactic acid.

# Biomaterials will play a substantial role in delivering a more sustainable status quo for chemicals production, as well as introducing the next horizon of performance to bring us into the future.

specialty-chemicals playbook for successful commercialization largely applies to these products.[3] Furthermore, sustainability presents many exciting new problems to solve through innovation—for example, not only reducing the embedded emissions in a car but also delivering new high-performance, bio-based chemistries that can further vehicle recyclability (via debondable adhesives) or increase the lifetime of batteries and enable fast charging (via heat dissipation).

## What it will take to succeed

Adhering to the following four principles will be critical for biomaterial players to gain a leadership position in the third wave:

**Excel at the fundamentals of cost and performance and partner with traditional chemical players to gain an edge**

For "bio-native" companies that have emerged around novel development and manufacturing processes, formulation of usable product forms and commercialization present new challenges that often have little to do with biological understanding. Yet established chemical companies with traditional, petrochemical-based products often have strong application understanding, formulation capabilities, and relationships with key customers. There is natural synergy in marrying greener (and novel) chemistries with the application-development expertise and market access of existing players to catalyze superior performance, cost, and customer relationships.

**Meet the nuanced needs and evolving sustainability concerns of customers**

Although GHG-emissions goals are a directional indicator, there is nuance within and beyond these targets. For example, how corporations define Scope 3 boundaries—cradle-to-grave versus cradle-to-gate[4]—can affect the relative sustainability benefits of biotech, or fermentation-derived materials, versus biomass-derived materials, for which most processing steps are identical to the petrochemical route. This means that non-GHG sustainability goals, such as renewable content levels or biodegradability, will affect the value proposition of any given biomaterial.

Biomaterial players must recognize that as corporate commitments rise over time so too will other routes to more sustainable materials. In short, the bar is rising and competition is intensifying. After all, other materials can also deliver GHG reductions. To maintain an edge, biomaterial players should leverage the latest tools of the Bio Revolution and continue to prioritize process innovation to fulfill a variety of ESG goals and sustainability criteria.

[4] "Cradle to grave" refers to a company's responsibility for dealing with carbon emissions from creation to disposal, whereas "cradle to gate" refers to the emissions impact of a product from production to sale.

Continued identification and incentivization of more sustainably farmed carbon feedstocks, for example by unlocking the potential of cellulosic biomass,[5] is necessary to further improve the environmental footprint and cost-effectiveness of biomaterials.

**Derisk investments through business models and demand commitments**

A frequent challenge in biomaterial commercialization is the financing of expensive capital projects, which, just as in petrochemicals, can cost several hundred million dollars. Given that the investment risk is even higher for first-of-their-kind plants, the result is that many promising biomaterial technologies only exist at pilot scale. Public purchase agreements between a consumer brand and a biomaterial company are becoming increasingly common before plants are even built, which can be a simple way to reduce uncertainty and investment risk. Thus, by identifying offtakes for a significant portion of planned volumes ahead of time, biomaterial players can make business cases more palatable for financers and partners alike.

**Provide clarity and transparency to stakeholders on sustainability attributes**

Corporations and consumers encounter a wide variety of labels and branding around the chemicals and materials that go into products. The term "biomaterial" itself can be confusing, sometimes referring to materials of biological origin and other times referring to biodegradable, fossil-derived products. Greater consistency and alignment across the chemicals and materials industry around labeling can help shift the conversation away from definitions and toward the merits and the metrics that allow biomaterials to compete on a clearer playing field.

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If biomaterial and chemical players can execute on these principles, biomaterials will play a substantial role in delivering a more sustainable status quo for chemicals production, as well as introducing the next horizon of performance to bring us into the future.

[5] For more, see Simon Alfano, Federico Berruti, Nicolas Denis, and Alberto Santagostino, "The future of second-generation biomass," November 2016, on McKinsey.com.

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