

pollution. Raising funds from plastics producers would align with the “polluter pays” principle and resemble a liability mechanism (14). It is important that the agreement ensures equity by helping countries to place the burden on the industry responsible for plastic pollution rather than the consumer. This can be achieved by encouraging the use of market-based instruments that target upstream measures, such as a levy on domestically produced virgin plastics, both generating funds and disincentivizing the excessive use of plastics. Ideally, these are earmarked levies channeled to fulfill the obligations of the agreement including by supporting research, development, and use of benign alternatives.

At the national level, a plastics authority should be designated to ensure the implementation of the agreement. The authority would be responsible for translating the internationally agreed sustainability criteria to the national context.

An evolving and inclusive framework

Not all relevant aspects can be addressed in detail in the agreement itself. A framework for further action will be needed, as well as institutional arrangements to redevelop rules and implementation arrangements. This includes a governing body to convene the contracting parties to adopt decisions, annexes, and protocols where necessary, including technical standards and guidelines on design and production, reuse, recycling, disposal, and retrieval. In addition, subsidiary bodies would be established for areas where scientific and technical support is needed, including defining criteria for the safe circularity of plastics and developing and facilitating use of harmonized methodologies for data collection. A science-policy interface should support the transfer of knowledge between expert communities and policy-makers (15).

Lastly, as the agreement is situated in a complex governance landscape, mechanisms would be needed to engage a wide array of societal actors and institutions. Specifically, a stakeholder engagement mechanism to facilitate nonstate and subnational action must support the agreement. This mechanism should include a global commitment platform where nonstate and subnational actors could announce voluntary commitments to be tracked and displayed online, and facilitate the organization of global and regional high-level events, technical dialogues, and other activities. These would allow learning from best-practice examples as well as from failures and to identify opportunities for upscaling ambition and action. A particular challenge will be to include the informal sector in the development and implementation

of the agreement—for example, waste pickers as a major component of waste management systems in developing countries. In addition, the agreement would need a coordination mechanism for enhancing cooperation and synergies with existing other multilateral environmental agreements and relevant frameworks.

NEXT STEPS

The decision to launch an intergovernmental negotiating committee lies with the UNEA. The next decision-making meeting (UNEA 5.2) is scheduled for February 2022. A preparatory Ministerial Conference is scheduled for 1 to 2 September 2021 on invitation by Germany, Ghana, Ecuador, and Vietnam.

It will take several years for a new agreement to be negotiated, enter into force, and begin to have an impact. Hence, it is necessary to continuously develop and strengthen action through existing regional and multilateral institutions. Yet governments need to boldly go beyond existing approaches. Although a new agreement will come with costs, it will unlock sizable environmental, social, and economic benefits (2, 8, 13). ■

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ACKNOWLEDGMENTS

The authors thank C. Dixon and T. Gammage (Environmental Investigation Agency), as well as three anonymous reviewers, for helpful comments. The authors declare no competing interests.

10.1126/science.abi9010

PERSPECTIVE

The myth of historical bio-based plastics

Early bio-based plastics, which were neither clean nor green, offer lessons for today

By **Rebecca Altman**

Bioplastics are a broad category of materials encompassing bio-based, biodegradable, or both bio-based and biodegradable plastics. They can be manufactured from diverse sources, including crops (e.g., corn, sugar cane, and, historically, cotton), wood pulp, fungi, and other bio-based feedstocks produced with the help of algae or microbes. Some bio-based plastics, such as polyhydroxyalkanoates (PHAs) and polylactic acid (PLA), are biodegradable under specific environmental conditions. Others, such as bio-polypropylene (bio-PP) and bio-polyethylene terephthalate (bio-PET), are also bio-based but are chemically equivalent to their conventional counterparts and do not biodegrade. Bioplastics can also include materials designed for biodegradation that are derived from fossil fuel-based rather than bio-based sources (1). Although bioplastics represent a small and growing segment within the industry, they are not a new idea and have a long history that is often overlooked or misunderstood.

The earliest iterations of industrial-scale molding materials date to the mid-1800s and were sourced from trees (e.g., resins, gums, and latex). Hard rubber and gutta-percha are two early examples. Later bio-based plastics were made using cellulose, including celluloid and viscose rayon (fiber) and cellophane (film). Despite their biological origins, these materials had consequences for human health and the environment, leading to displacement, deforestation, environmental degradation, and workplace hazards.

Popular accounts and even corporate advertisements from this era portray early-generation plastics relieving pressure on natural resources such as tortoise shell or ivory because they could imitate their appearance.

Independent researcher, Providence, RI.
Email: rebecca.altman@gmail.com

For instance, celluloid, a nitrocellulose plastic industrialized in the 1870s, purportedly spared the elephant, especially from the billiard ball industry; however, market data show that celluloid did not decrease ivory demand, which grew in the years after celluloid's introduction. Less well known is how celluloid accelerated the demand for camphor, a tree product used as a solvent and plasticizer. The camphor market intensified as celluloid production expanded toward the end of the 19th century, when the burgeoning photography and cinematography industries required celluloid for film (2).

Camphor was distilled from the camphor laurel tree, a species of evergreen especially prevalent in Taiwan, where the imperial regimes of China, Britain, and Japan vied for control over its production. The camphor trade decimated Taiwan's forests and displaced its Indigenous communities—most notably the Atayal peoples, who resisted the commodification of their homelands (3).

Likewise, gutta-percha, a rubber-like tree resin harvested across the latter half of the 19th century in the Malay archipelago and throughout Southeast Asia, was used to insulate the growing network of undersea copper telegraphy cables so instrumental in administering the British empire. On average, a single tree would produce less than a pound of gum. In a matter of decades, the region's gutta-bearing trees were harvested to near-extinction (4).

Rayon fibers are another 19th-century technology based on chemically regenerated cellulose sourced from cotton, cotton linters (remnants of cotton production), or wood pulp. Multiple rayon processes were developed first in the UK and then elsewhere. In the US, the viscose process (also used to manufacture cellophane) was dominant by the Second World War, the era in which annual global rayon production exceeded 2 billion pounds (5).

The pursuit of rayon as a forest product, for example, resulted in clear-cut sections of the Tongass National Forest, a temperate rainforest in southeastern Alaska. After passage of the 1947 Tongass Timber Act, the US Forest Service offered 50-year timber contracts and subsidized the construction of two mills on the unceded lands of the Tlingit, Haida, and Tsimshian peoples. The first mill, built in Ketchikan, went online in 1952. The largest US rayon producer, American Viscose, had a considerable stake in the venture. Major Japanese manufacturers such as Mitsubishi Rayon, Kokoku Rayon, and Teikoku Rayon invested in the second mill built in Sitka.

But deforestation and displacement were not the only consequences. Early bio-based plastics were also as hazardous to harvest as they were to transform into moldable materials, going back to hard rubber (e.g., vulcanite or ebonite). Industrialized in the 1840s after the development of vulcanization, hard rubber was made from caoutchouc (natural latex) extracted from multiple species found in the rainforests of South America and Southeast Asia. These were later husbanded through plantation economies, often violent and exploitative, as exemplified by the rubber plantations overseen by the regime of Belgium's King Leopold II in Congo (6). But whether wild or domesticated, harvesting latex was dangerous work.

The hours were equally long in low-wage rubber factories. Poor ventilation exacerbated workers' exposure to a steady stream of toxic



In the 19th century, rubber trees provided latex for hard rubber, an early molding material, but as with other bio-based plastics, required additional chemical inputs—some toxic, others extracted under colonial regimes.

feed materials, including naphtha and carbon disulfide. From the outset, vulcanized rubber production caused a range of acute and chronic neurological issues, including mental health effects so severe that in extreme cases, workers were institutionalized. The idiom “to be gassed” originates from early rubber factories (7). Despite substantial evidence of its toxicity, carbon disulfide became instrumental to viscose rayon and cellophane production, too. As a result, successive generations of viscose workers into and across the 20th century also experienced neurological as well as cardiovascular effects (8).

Occupational hazards extended to other classes of early bio-based plastics as well. Nineteenth-century celluloid factories were notoriously prone to explosion, conflagration, and worker injury (9). Pulp mills, such as the Ketchikan mill built in

the Tongass, used a noxious sulfite process to convert chipped spruce and hemlock into dissolving pulp. Over its lifetime, the mill racked up hundreds of environmental violations before closing in the 1990s. By then, area health professionals had appealed to state epidemiologists to investigate possible links between mill pollution and conditions prevalent among their patients. Eventually, the mill was subject to both civil and criminal investigations. Further, the environmental legacy of rayon-grade pulp in the Tongass includes dioxins, heavy metals, and polychlorinated biphenyls (PCBs) (10).

Natural and semisynthetic plastics were followed by a generation of fossil fuel-derived synthetics. Bakelite, invented in 1907, marked this passage and eventually replaced ivory in pool halls. Bakelite was made from the reaction of coal tar-derived phenol with formaldehyde synthesized via methanol. By the 1920s and early 1930s, a new class of vinyl plastics was also in development. One among several progenitor vinyls was Union Carbide's Vinylite, a copolymer of polyvinyl chloride and polyvinyl acetate, based on mixed feedstocks, notably ethane (a natural gas liquid). Further, Carbide's development of the then-new field of ethylene derivatives, which later capitalized on the hydrocarbon by-products of petroleum production, coupled with the rapid expansion of refinery and plastics manufacturing capacity catalyzed by the Second World War, helped facilitate the industry-wide transition toward the petrochemical-dominant plastics of today (11).

But the advent of these fossil fuel feedstocks did not immediately eliminate prior biomass sources. Viscose is one example. Leading into the war, plastics were also an agricultural product, making use of farm waste or farmed products, a field called chemurgy (12). Early proponents included George Washington Carver and Henry Ford, who envisioned an integrated forest-farm-factory system. Ford purchased not only a rubber plantation in South America but also large tracts of farmland and timber stands in Michigan's Upper Peninsula, where wood pulp was converted in the chemical distilleries at Iron Mountain into automotive paints and artificial leather.

In general, 20th-century plastics tended to follow available raw materials, both geographically and across time. As nations shifted their energy and industrial systems, plastics manufacturers diversified feed material to make use of systemic by-products or

waste products. One recent example is how some US plastics producers converted from crude oil or naphtha-based feedstocks to ethane, a by-product of natural gas production through hydraulic fracturing.

The transition to renewable energy opens the question of which substrates will be used for future plastics. Understanding plastics' early industrial history is important because these bio-based products established the political-economic relations of modern, conventional plastics and portended problems to come. This history also points to the insufficiency of an ahistorical technological fix, such as swapping in alternative carbon sources, which may not improve plastics' ethics, safety, or sustainability. This is especially true if the same problematic chemistry is used to modify the base plastics' performance characteristics (13). For example, even if viscose/rayon is sourced from Forest Stewardship Council (FSC)-certified forests, its production may still rely on carbon disulfide.

To avoid such problems, it is necessary to rethink the premises on which plastics technologies have been developed and produced. Critical adjuncts include reengineering plastics for recovery and reuse, augmenting recycling infrastructure (14), and source reduction and dematerialization. This means making fewer plastics by developing alternatives to their short-term, disposable uses, which presumes land access for landfills (i.e., long-term storage of solid waste or ash) (15). The challenge for bio-based plastics research is to account for this history and to think critically about the supply chains required by plastics currently in development, including a focus on ethical, sustainable feedstocks; toxics reduction and safer materials; and worker and community health and safety. ■

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10.1126/science.abj1003

PERSPECTIVE

Achieving a circular bioeconomy for plastics

Designing plastics for assembly and disassembly is essential to closing the resource loop

By Sarah Kakadellis¹ and Gloria Rosetto²

The visual nature of plastic pollution and the scandals of plastic waste exports to developing countries have prompted a shift in how plastics are made, used, and disposed. Plastic waste remains poorly managed, with as much as 12,000 million tonnes projected to have accumulated in landfills or the natural environment by 2050 (1). Although mechanical recycling was initially promoted as the solution to rising amounts of postconsumer plastic waste, its failure over the past decades has exposed the severity and scale of the plastic waste management crisis. In light of this, the recovery of plastics through chemical recycling—polymer recycling into their constituting repeat units or monomers (and oligomers)—and the development of bio-based and biodegradable alternatives have gained increasing attention. We consider the technical, chemical, and biological routes to closing the loop and argue for an integrated plastic waste management system rooted in the circular bioeconomy.

Shunning fossil-based plastics has provided a fertile ground for the emergence of alternative materials, loosely referred to as "bioplastics." Despite favorable public opinion, consumer awareness and understanding of the subtleties in the terminology is poor (2). The term bioplastics is an umbrella designation that captures a range of polymer chemistries, properties, and application sectors. It encompasses two distinct concepts: the bio-based origin of the raw materials and biodegradability at the end of life. Bio-based sources are necessary for divesting from fossil fuels. However, life-cycle analyses have uncovered complexities in the system, mostly owing to agricultural inputs for bioplastic feedstock production (3). Recent approaches using waste or coproducts from the biomass sector as feedstocks offer attractive alternatives.

Some (fully or partly) bio-based plastics, such as bio-polyethylene terephthalate (bio-PET), are chemically identical to their fossil-based counterpart, making them suitable for the current recycling infrastructure. However, biodegradability tends to be perceived as more sustainable over (mechanical) recyclability by consumers (2). The biggest advantage of biodegradable plastics may not be their biodegradability per se but their compatibility with food waste, opening new streams for plastic waste management positioned around organics recycling (3). Nevertheless, issues associated with separation and contamination in existing mechanical recycling streams and concerns over their complete biodegradability in the current organic waste management infrastructure remain (4).

Although biodegradable plastics can return carbon and nutrients to the soil, the energy and resources associated with their production is effectively lost, echoing the linear flow of petrochemical plastics in single-use applications. Maintaining a closed-loop resource flow appears more sustainable. Yet, 67% of plastic waste generated in the UK consists of hard-to-recycle packaging (6). Across Europe, only 42% of plastic waste generated is collected for recycling (5, 6). Failing market incentives for plastic recycle have led to many plastics being exported to Southeast Asia, where they are often disposed of in illegal landfills (7).

Thermochemical processes, such as pyrolysis and gasification, have emerged as an alternative recycling strategy for the recovery of plastic waste—notably, hard-to-recycle plastics (6). Although they are often referred to as chemical recycling, these processes are not selective for monomer retrieval, producing a wide range of hydrocarbons and carbon dioxide (CO₂). Further separation and transformation steps are required that are energy intensive. By contrast, closed-loop recycling to monomers (CRM) can be seen as ultimate chemical recycling in that it ensures the recovery of a given polymer's building blocks.

The feasibility of CRM is greatly dependent on polymerization-depolymer-

¹Centre for Environmental Policy, Imperial College London, London SW7 1NE, UK. ²Department of Chemistry, University of Oxford, Oxford OX1 3TA, UK. Email: sarah.kakadellis14@imperial.ac.uk

The myth of historical bio-based plastics

Rebecca Altman

Science **373** (6550), 47-49.
DOI: 10.1126/science.abj1003

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