Into the Future with Biopolymers

How Bio-Based Polymers Can Help Sequester CO_2 for the Long Term

Biodegradable and bio-based plastics are suitable for more than just ephemeral products such as compostable packaging and bags. While the contrary impression may be gained from the intensive reporting surrounding plastics polluting the environment, they do offer major benefits. Bio-based plastics can lock away vast quantities of CO_2 in durable, recyclable applications and make a real contribution to climate protection. All that is needed for this is the right product design and a functioning circular economy. By focusing more on this approach, the plastics sector has the chance to evolve into a key industry of a green economy.

Plastics possess very good properties that make a wide range of applications possible. However, it takes extensive quantities of the fossil raw materials oil, gas and coal to make them. Plastics account for 6% of annual global oil consumption, and when they come to their end of life, they then generate vast amounts of waste that is often difficult to reuse or to recycle. Hand in hand with this, they are responsible for the emission of millions of tons of CO_2 that contribute to global warming. True, these emissions can be reduced by extending their service life and using recycled materials, but this is still difficult to achieve in many applications. An alternative is to use bio-based plastics made from renewable raw materials because, unlike fossil raw materials, the carbon bound up inside them is naturally carbon- or climate-neutral.

The public conceives bioplastics as being mainly thin, compostable bags, i.e. shopping bags and bags for collecting organic waste. Food service packaging and carrier bags are currently under fire as symbols of the wasteful and disposable society. This negative image has not only led to criticism, but also given rise to specific legislative measures. The European Directive on single-use plastics bans disposable cutlery and plates, EPS drinks containers, straws and plastic cotton buds. And it includes packages of measures governing a swath of products, such as drinks cups, cigarette filters, outer packaging and closures.

Furniture and furnishings with a long service life are the ideal applications for bioplastics

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The Single-Use Plastics Directive makes no exemptions for biodegradable plastic products, unlike EU Directive 2015/720, which targeted only plastic carrier bags. Under the latter, EU Member States may choose to exempt compostable carrier bags with a wall thickness below 50 µm from the wide-ranging reduction targets.

In Italy, this has led to the creation of the largest national market for biodegradable and compostable plastic bags, which are used first for shopping and then for collecting organic waste. The market has a volume of around 60,000 t, while the total market in Europe in 2020 for such plastic bags and the ultra-thin, semi-transparent organic waste bags is estimated at around 150,000 t. However, exact figures and statistics on this are unavailable.

The bags are mostly composed of compounds derived from biodegradable co-polyesters such as polybutylene adipate terephthalate (PBAT), polybutylene succinate terephthalate (PBST), and polybutylene succinate (PBS), which are manufactured with vegetable starch or other polymers such as polylactic acid (PLA).

New Applications Sought for Biodegradable Polymers

These plastic film products can likewise serve in the packaging market as water-vapor-permeable, breathable films for packaging fresh food. The polymers or compounds are also used for boxes that are coated by a variety of processes and their purpose is to act as a grease or protective barrier against volatile organic compounds (VOC). Unlike in the bags market, however, their share of the food-film segment of the market is still very small, lying in the parts per thousand range. Preventing their wider adoption is their cost, which is usually more than twice that of film made from commodity polyethylene (PE) or polypropylene (PP). Added to which, PLA or PBAT film grades are now classified as "not recyclable in practice." Consequently, users interested in them are sticking for the moment with single-resin films made from PE, PP or polyethylene terephthalate (PET). Although the bulk of these, too, are still thermally recycled, the possibility of sorted collection and thus mechanical recycling at least still exists. Such systems are already in place for polyolefins and PET, but not yet for PLA and other biodegradable plastics.

Composting of biodegradable plastic packaging is currently banned in Germany. It is thus shut off from this recycling route, which would otherwise make sense for selected products at least. The same trend is starting to emerge in other EU countries, which had been more open to this recycling route up to now. Although Section 21 (1) 2 of the German Packaging Act expressly regulates incentives aimed at favoring the use of recycled material and renewable raw materials by what are known as the dual systems, express legislative measures to date have been directed at recyclability only. The basic legislative supports may be in place, but the mechanisms necessary for providing a boost in practice and generating lasting effects are still lacking.

Fig. 1. Jackets could be a good end use for bio-based fibers before they are chemically recycled. Tierra, a Swedish sports goods manufacturer, already offers outdoor jackets made from 100 % bio-based PA11 © Tierra

With market and authorization conditions for biodegradable plastics in this segment becoming increasingly obscure, manufacturers are faced with the challenge of developing new application areas and recycling routes. Biodegradability could be an advantage in outdoor applications such as mulch films or growth covers. These polyesters have, moreover, an interesting chemical structure and the packaging sector, for instance, is researching their ability to act as oxygen barriers and to afford VOC and aroma protection. An example of what companies can do when they put their minds to something is Ekoplaza, a Dutch organic supermarket chain. It boasts more than 100 compostable packaging solutions which it has developed as part of its #PlasticFree campaign. These include simple pouches, paper-PLA window combinations for baked goods, packaging film for dry foods, and even complex packaging for fresh meat, and potato chips. This situation contrasts with that in the German market, where biodegradable plastics occupy only microniches, such as cellulose films for chocolate.

High Demand for Drop-In Variants

The packaging sector, which is the largest plastics segment, has much greater hopes for drop-in bioplastics. These plastics are structurally identical with fossil-based feedstocks, but are made from renewable raw materials. Bio-based PE and 30% bio-based PET have been commercially available on a scale of hundreds of thousands of tons for ten years and are currently almost sold out. Both can be used for any application for which a type specifi- »

Fig. 2. Toy bricks are often used for years. They are therefore a logical first application for bioplastics. Lego now uses bio-based polyethylene for some of its toy bricks © Lego

Fig. 3. Sports pitches could be an intermediate use for bioplastics in a holistic use scenario. Polytan-Sportsgroup's sports turf carpets, e.g., are made of bio-based PE © Polytan-Sportsgroup

Fig. 4. Cellulose acetates or bio-based PA11 are suitable for spectacle frames © Harald Käb

cation for the numerous polymer variants exists. Their ease of recycling depends only on the design of the product. Their key advantage is their reduced carbon footprint. Numerous brand-name companies have signed up to climate protection and set themselves specific savings targets. Bio-based polyolefins and PET can help them to close in on these targets, while keeping additional costs fairly manageable.

Technological progress in drop-in biopolymers would be boosted if their advantageous carbon footprint could be translated into a pricing advantage. For example, if CO_2 pricing measures or climate taxes were to factor in the carbon bound in materials, biopolymers, which are mostly more expensive at the moment, would start approaching fossil-based plastics in terms of price.

Politically Insensitive

The chemical and plastics industries already have wide-ranging access to these polymers. The established route to PE via bioethanol or ethylene glycol (MEG) in PET could be supplemented by biomethane (biogas), or bionaphtha (from waste grease or vegetable oil residues). The chemical plants needed to do this already exist; manufacturers would need only to feed these biogenic feedstocks into their integrated production sites and crackers. The outcome would be a quantum leap in the development of a chemistry based on renewable raw materials akin to that experienced by the energy sector through legislative support for renewable energy generation. The raw material potential is considerable: with increasing electrification of the transport sector, the high-volume biofuels and the energy carrier biomethane could become the chemical feedstocks of the future and would be available on a scale of millions of tons. The first steps have already been taken. Collaborative work between Neste, in Espoo, Finland, LyondellBasell in Rotterdam, Netherlands and Ikea in Delft, Netherlands, shows that this is a way to also produce what were previously inaccessible polymers. 30% bio-based PP is now available thanks to feed-in and cracker chemistry, and furniture giant Ikea is already using it for its products.

Industrial-scale chemistry based on renewable resources instead of oil, gas or coal would also be less sensitive to political crises. Biomass would be grown locally and not delivered in pipelines or tankers from politically unstable countries. Not only that, but the portfolio of bio-based polymers would be virtually unlimited. To the PE, PP and PET variants already available could conceivably be added bio-based variants of polystyrene (PS), polycarbonate (PC), and acrylonitrile butadiene styrene (ABS). Feeding biogenic base raw materials into large integrated production sites and further distributing them via the chemical industry's pipeline network would lead to substantial growth in the range of available bio-based polymers. In addition to biotechnology and CO_2 chemistry, i.e. the direct use of CO_2, the chemical and plastics industry, which is literally "fossilizing" at the moment, would in the course of just a few decades evolve into a key industry of the future, one that – in addition to its technical accomplishments – would be fully committed to sustainability.

There could be greater justification for using biomass in the chemical and plastics industries instead of in the energy and fuel sector. As a plastics feedstock, it would bring much more added value, and the time taken for the biogenic carbon to revert back into atmospheric CO_2 would be stretched out enormously. Not only would durable plastic applications such as building or furniture products be an option here, but the captured CO_2 could be put to good use for decades if the processes of reuse, repair and recycle were to be exploited to the full.

CO_2 Sequestration in Products

This kind of cascading use of materials would significantly extend the service periods for CO_2 and could act as a form of CO_2 sequestration while still allowing active use. At present, CO_2 sequestration regulations stipulate storage for at least 100 years, and only forests (in the form of timber), soils and oceans are permitted for this purpose. However, polymeric materials could easily be used to sequester for periods of 30, 50 or even 100 years,

Fig. 5. Manufacturers of electrical goods are also planning to use bioplastics for their appliances. Elektrolux, for example, recently presented a concept refrigerator made of bio-based plastics © Elektrolux

depending on the application. Given a properly functioning recycling loop, as exists in the case of PET, the service period could be extended even further. It is time for the sequestration regulations to be reviewed.

The 1.5 °C global target for combating the increasingly urgent climate problem no longer makes such concepts seem like a green utopian pipe-dream. Such a change can be effected in a short time – witness the swift transition in the energy sector and the transformation that is currently sweeping over the automotive industry as a result of electric mobility. There is huge pressure to change and it will only increase, because climate change has quickly become a climate emergency. In order to respond with the necessary alacrity, companies should learn to think holistically, in systems, and to review their entire value chains.

This approach is illustrated by the following example: bio-based PET bottles circulate within a reuse and mechanical recycling loop. Having reached the end of this loop, they find high-value application in the fibers segment, e.g. as outdoor jackets (**Fig. 1**) or as carpets in the automotive and residential sectors. After that, the fibers are chemically decomposed back into their monomers – ready for use all over again. All this is already technically feasible today, can be accomplished with relatively low losses and has a very beneficial effect on the carbon footprint. It just needs to be organized.

Cascading Use of Bioplastics

Such extended-use scenarios could also be conceived for PE. Years of initial use as building blocks in the toy sector –Lego in Billund, Denmark, already uses bio-based HDPE in this way (**Fig. 2**) – could be followed by conversion to another product, e.g. a sports turf (**Fig. 3**) that lasts for 15 years, with subsequent removal and conversion into composite grass block pavers. This would be a way of locking up atmospheric CO_2 as bio-based carbon for decades.

With a few exceptions, bio-based plastics are relatively novel polymers that are in the early stages of widespread commercialization. Cellulose acetate (CA), which dates from 1865, is currently by far the most ubiquitous bio-based plastic. It is used to manufacture a wide range of products, such as photographic film, spectacle frames, cigarette filters and coatings (**Fig. 4**). No other thermoplastic or thermoset biopolymer is used on a comparable scale of millions of tons. Unfortunately, there are very few reliable market reports or official statistics available on biopolymers. The only way to deduce where they are already being used is to look at specific examples.

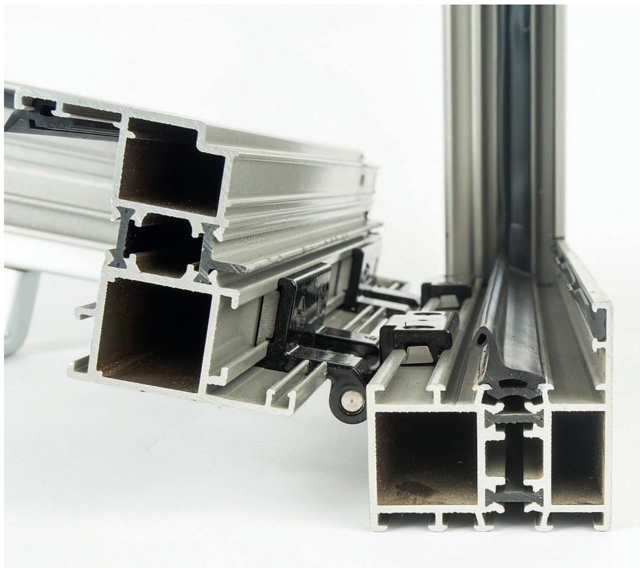

Fig. 6. Bio-based TPE are mainly used for technical applications, e.g. as sealing strips for window profiles

PLA: Versatile and UV-Resistant

PLA, a polymer that has become known as film or cup plastic, is one of the most versatile bioplastics. PLA can unfold different properties in a number of structural polymer variants and can be used for housings of electrical and electronic products such as refrigerators (**Fig. 5**) and laptops. Its good processing properties have quickly made it popular with designers and hobbyists who use it as a filament for 3D printers. 3D printing can be used to create individual figures for games or items for the home. Privacy roller blinds and sun blinds made from PLA are used in offices, because the polymer has very good UV resistance and has little need of additives. PLA fiber also has good breathable properties, and hence it is used for bedspreads and textiles. These products are furthermore considered anti-allergenic and harmless to health because they are free from interfering substances. In the current coronavirus pandemic, PLA is also being used to make transparent face shields. PLA can be recycled mechanically and chemically. However, this requires economic recycling systems, which will only become viable at higher market volumes.

Polytrimethylene terephthalate (PTT), a polyester related to PET, can be produced from 1,3-propanediol, which is biotechnically accessible and has one more carbon atom than monoethylene glycol. Fibers made from PTT are extremely durable and so are found in high-quality carpets and textiles.

A whole range of partially or fully bio-based polyamides (PA) can be considered both as high-performance fibers and as compounds for demanding melt-processing applications. PA11 is produced chemically from castor oil and can be used, for example, as a fuel line in vehicles. PA4.10 finds application as engine covers, among other things, while PA6.10 and 6.12 serve in numerous highly specialized technical applications such as compressed air brake lines and dowels.

Bio-Based TPE and TPU

Bio-based thermoplastic elastomers (TPE) and polyurethanes (TPU) rank among the newer bioplastics more likely to be used in technical applications (**Fig. 6**). Their biogenic content varies considerably, depending on the composition and formulation in the end product. The end products are usually composed of different materials, which is why the bio-based content also varies greatly. In many cases, manufacturers do not provide specific information about the level of biogenic content. However, it nearly always comes from a green polyol component. »

Such bio-based polyols exist in surprisingly large numbers. The spectrum ranges from sugar-based building blocks, to fermented diols, to triglycerol through to fatty acid derivatives obtained from vegetable oils. TPE are mostly elastomers of complex composition, e.g. polyetheramides. TPE have cushioning and resilient properties which make them suitable for use in sports goods, as well as for bath mats, and soft parts for toy figures. TPU are also often found in the areas of sports and hiking. Global consumption in footwear alone, whether as soles, insoles or cushions, is estimated at over 700,000 t/a. Many footwear manufacturers are now using soles and other components with a bio-based content for soccer shoes and hiking boots (**Fig. 7**). The sports goods industry has discovered bio-based polymers for itself, as many of its customers are consumers who are highly concerned about plastics.

Although there is great potential in both areas, bio-based polymer products have so far made little headway in the furniture and construction industries and are not expressly advertised. The latter is due to the fact that many products have only a small content of bio-based components.

It is not at all uncommon to find bio-based polyols in polyurethane formulations (PU), e.g. in construction foams and in adhesives. The bio-based monomer epichlorohydrin (ECH), obtainable in large quantities from glycerol, itself a by-product of biofuel production, is also employed quite often in epoxy resins due to its good price competitiveness. Polyepoxides act as adhesion-promoting components in many durable composite products. They are equally likely to be found in aircraft construction and wind turbine blades as in skateboards and surfboards. Bio-based PU are the preferred choice for flexible foams, such as for upholstered seats and mattresses. Although there are many individual products, these markets or polymer types have never been systematically screened for renewable polymer types. It is obvious that market opportunities are there, because there is now also a "green variant" for most end products.

Greater Potential than Just for Niche Applications

As already mentioned, reliable market data on the consumption of bioplastics in the various sectors is still scarce. In any case, many applications are still small-volume niches. However, the potential is often much greater for numerous reasons.

Climate Protection and Circular Economy as a Development Priority

The lack of reliable market information is also a hindrance to supportive legislation, which is often the reason why innovations break through to the market in the first place. In the case of biodegradable plastics, it is easy to see how crucial legislation is in relation to market introduction. However, it is not necessarily always political and societal debates that create good boundary conditions for innovations. With biodegradable plastics, it was the pressure exerted on unpopular products such as carrier bags and disposable tableware that forced market developments initially. The industry believed it could escape the pressure by turning to compostable, biodegradable products. Demand such as this acts as a huge incentive for manufacturers of such polymers looking to invest and grow. The problems arise when the arguments fail to both silence the criticism and justify exceptions made to statutory reduction targets. The producers of biodegradable plastics are now faced with the difficult situation of looking for new fields of application in Europe, because the days of disposable carrier bags and tableware are numbered. They have failed to position biodegradability and compostability as offering decisive advantages.

A successful outcome would more likely be achieved by presenting functionality in conjunction with strong ecological arguments and seeing the products as being useful and important rather than superfluous. Bio-based plastics as an innovation will only show off their strengths to full effect when manufacturers embrace holistic systems thinking and align their market positioning accordingly. The circular economy and the primacy of climate protection provide the framework for development and promote marketing on a wide scale. The ideal applications would be bio-based plastics – not just at the time of their market launch – which are contained in high-quality, maximum durability products which can be recycled in a cascade of processes into further products.

Fig. 7. Hiking boot with sole made of bio-based TPU: footwear manufacturers are increasingly turning to bioplastics due to their customers' high concern for climate protectiont © VauDe

The entire plastics industry needs to rethink its position and is, in fact, already starting to align itself with these principles. Its future is as much in doubt as that of the fossil fuel industry and of diesel and gasoline-powered vehicles. Some of the solutions are already waiting in drawers and some, in small doses, are already on the market. The smarter the concepts and the greater the will that is shown by major players, the faster the breakthrough on a broad front will occur. ■

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