Cell Press REVIEWS

Review

Green Bioplastics as Part of a Circular Bioeconomy

Hakan Karan,[1,4] Christiane Funk,[2,4] Martin Grabert,[3] Melanie Oey,[1] and Ben Hankamer[1,*]

The rapid accumulation of plastic waste is driving international demand for renewable plastics with superior qualities (e.g., full biodegradability to CO_2 without harmful byproducts), as part of an expanding circular bioeconomy. Higher plants, microalgae, and cyanobacteria can drive solar-driven processes for the production of feedstocks that can be used to produce a wide variety of biodegradable plastics, as well as bioplastic-based infrastructure that can act as a long-term carbon sink. The plastic types produced, their chemical synthesis, scaled-up biorefinery concepts (e.g., plant-based methane-to-bioplastic production and co-product streams), bioplastic properties, and uses are summarized, together with the current regulatory framework and the key barriers and opportunities.

Highlights

Fossil fuel and plastic production are currently integrated.

About 80% of manufactured plastic accumulates as waste in landfills and natural environments, presenting an increasing hazard.

Biodegradable and bio-based plastics present a viable and attractive alternative.

Well-crafted legislated standards on plastic biodegradability and environmental and animal/human health impacts could fast-track and optimize industry transition.

The diversity of bio-based feedstocks opens up the opportunity to produce an expanding range of renewable plastics.

Biodegradable plastics should ideally fully degrade to CO_2 and water without harmful byproducts.

Durable bioplastics can act as carbon sinks if well integrated into large-scale long-term infrastructure.

Biorefinery and GMO strategies can support viable business development and the emerging circular bioeconomy.

The Build-up of Plastic Waste

In 2017 the global economy was valued at US$127 trillion[i] [gross domestic product (GDP), purchasing power parity] and was powered by an energy sector valued between US$6.35 and US$17.78 trillion (historically 5%–14% of the GDP) [1] mostly through the use of petrochemical fuels [2]. The petrochemical industry is highly integrated and approximately 80% of all the non-fuel chemical byproducts by weight are reportedly used in the manufacture of polymers [3]. Total cumulative global plastic production up to 2015 exceeded 8.3 Gt and resulted in 6.3 Gt of plastic waste [4]. By 2050, this waste is expected to increase toward 12 Gt [4]. The 6.3 Gt of plastic waste produced to date can be calculated to have a volume of approximately 5.9 km^3 using their average plastic densities (see Supplemental Table S1 online). This is enough to build 2269 plastic replicas of the Great Pyramids of Giza and can be calculated to contain 240 EJ (0.24 ZJ; about half of our total global annual energy demand [5]). Of this waste (6.3 Gt) only 21% has been recycled or incinerated [4], whereas the remaining 79% either entered landfill or was released into the environment.

Perhaps the most graphic example of the global scale of plastic pollution is **the Great Pacific Garbage Patch** (see Glossary), which covers an area of around 1.6 million km^2 and is expanding rapidly [6]. It is one of five such patches formed due to complex oceanic currents and has a consistency of a plastic soup [7]. Most particles within this soup have a diameter of a few millimeters [7]. At least 5.25 trillion plastic pieces are now reported to float in world oceans [8]. Particles bigger than 5 mm account for 87% of the weight of this plastic waste [8]. By contrast, particles with a diameter of 1.01–4.75 mm are the most common [8] and classed as **microplastics** (i.e., less than 5 mm in diameter[ii]). Microplastics account for about 13.2% of plastic waste by mass [8] and concerns regarding health-related problems are increasing due to their entry into the food chain. Commonly consumed human food sources such as fish, bivalves, and crustaceans have been reported to ingest microplastics [9]; microplastics have also been found in salt, beer, honey, salt, sugar, and bottled water [9]. Despite literature gaps,

[1]Institute for Molecular Bioscience, 306 Carmody Road, The University of Queensland, Brisbane, QLD 4072, Australia
[2]Department of Chemistry, Umeå University, SE-90187 Umeå, Sweden
[3]Montroix Pty Ltd, PO Box 4394, Hawker ACT 2614, Australia
[4]Joint first author

*Correspondence: b.hankamer@uq.edu.au (B. Hankamer).

exposure to microplastics through diet or inhalation may be causing an increase in complications in diseases such as inflammation, cancer in animals, and toxic effects (especially humans) due to bioaccumulation [10] (see Outstanding Questions). Consequently, health and environmental degradation are uncosted externalities.

The increasing demand for plastics and the fact that some types are estimated to take longer than 100 years to fully degrade (estimate only, due to insufficient time-series data) highlight the need to either reduce plastic use (difficult without legislation) or replace nondegradable plastic with sustainably produced and degradable bioplastics. **Bio-based plastics**, as part of an expanding circular bioeconomy, can be designed to be either totally biodegradable to CO_2 in a matter of months or years [11], or contribute to carbon capture and storage through integration into nondegradable long-term infrastructure [12], including plastic-based municipal water and sewer piping, building and roofing materials, and road surfaces.

As approximately 80% of nonfuel chemicals produced by the petrochemical industry are sold for the manufacture of plastics [3], recent fossil fuel investments in the United States and Europe (mainly due to the fracking boom), as well as in China, may result in petrochemical plastics production being locked-in for several decades from as early as 2025 [13], unless appropriate legislation is passed and the bioplastics industry gains significant traction. Currently approximately 99% of plastics is produced through petrochemicals [14]. China's announcement that it would no longer accept international plastic waste for recycling from December 31, 2017, has exacerbated this problem and increased the need for sustainable **bioplastic** solutions, as by 2030, 111 Mt of plastic waste will be displaced through this policy change [15]. This review summarizes current plant-based and emerging microalgal- and cyanobacterial-based bioplastic production options, as these offer a series of advantages that contribute to **UN sustainability goals** (i.e., Good Health and Well-Being, Clean Water and Sanitation, Affordable and Clean Energy, Decent Work and Economic Growth, Industry, Innovation and Infrastructure, Sustainable Cities and Communities, Responsible Consumption and Production, Climate Action, Life below Water, and Life on Land)[iii].

Bio-Based Plastics

Currently, most bioplastics are produced from agricultural crop-based feedstocks (carbohydrates and plant materials). These, however, are not yet ideally aligned with the UN's sustainable development goals (SDGs), due to their competition for arable land, fresh water, and food production [16]. Next-generation microalgae-based bioplastic production can theoretically address many of these issues, as they can be located on nonarable land. This expands global photosynthetic capacity, can be seen as a much-needed technology-assisted reversal of desertification, and increases our ability to convert CO_2 into feedstocks for bioplastics. Microalgae systems can also use saline and/or wastewater and enable effective recycling of nutrients (e.g., nitrogen and phosphorous) in contained systems, thereby reducing eutrophication and reliance on energy-intensive chemical fertilizers. Unlike fossil-based plastics, microalgae-based bioplastics can be designed for biodegradability in natural as well as industrial composting settings. Although biodegradable fossil-based polymers such as polybutylene adipate terephthalate and polycaprolactone exist [17], their production from petrochemicals precludes them from being CO_2 neutral. Internationally, microalgae systems also offer the technical capacity to support distributed production, while locally they offer the potential to enable regional communities to be more self-sufficient and provide significant new market opportunities (SDG, Decent Work and Economic Development). If strategically developed, these systems can therefore provide sustainable solutions and make a significant contribution to a number of the UN SDGs.

Glossary

Bio-based plastic: plastic generated from renewable biomass sources (i.e., derived from plants or microorganisms). Bio-based plastics have properties equivalent to their fossil-based counterparts and at the same time they reduce the product's carbon footprint.

Biodegradable plastic: biodegradation is a chemical process performed by microorganisms, which metabolize materials into CO_2, water, and/or methane. Biodegradability is dependent on various factors including temperature, humidity, the surrounding microbiome population, as well as the environment (terrestrial or aquatic locations) and light, which can drive photodegradation; the time frame for degradation can therefore vary considerably. Biodegradation can be performed by industrial composting, garden compost, in soil, or in water (fresh, brackish, and seawater); of these only industrial compostability is currently described in standards, as the conditions and time frames can be clearly specified.

Bioplastic: a diverse family of materials, which can be divided into three main groups: bio based; bio based and biodegradable; and plastics based on fossil fuels that are biodegradable.

Great Pacific Garbage Patch: also described as the Pacific trash vortex, the Great Pacific Garbage Patch was reported as early as the mid-1980s in the North Pacific Ocean. It consists of an accumulation of floating debris dispersed over a large area in the upper water column. Similar patches were discovered in the other four gyres (e.g., in the North Atlantic).

Microplastic: small pieces of plastic with a diameter below 5 mm. Primary microplastics are a direct result of human-manufactured material and use, while secondary microplastics are breakdown products of larger plastic debris. Both types persist in the environment at high levels, particularly in aquatic ecosystems, enter the food chain, and may accumulate in tissues.

UN sustainability goals: 17 global goals were set by the United Nations in 2015 with the formal name 'Transforming our World: the 2030 Agenda for Sustainable

The molecular complexity of plant and bacterial biomass provides a wealth of natural bio-based polymers as well as monomeric feedstocks for bioplastic production. Figure 1 summarizes the main classes of currently developed bio-based plastics. These include plastics based on starch, polyhydroxyalkanoates (PHAs), polylactic acid (PLA), cellulose, renewable polyethylene and polyvinyl chloride (PVC), as well as protein-based polymers. The left-hand column (Figure 1) provides the chemical formulae of naturally occurring monomers and polymers, which represent the inputs for production of each of these bioplastic types. These monomers and polymers can be sourced from higher plant crops as well as microalgae and cyanobacteria. Example conversion processes of the natural monomers and polymers to their respective bioplastics are summarized in the middle column. The right-hand column provides a property summary of each plastic class, as well as published examples of their uses and degradability characteristics. Because of the very large number of combinations in which the monomers can be mixed, cross-linked, and their properties modified through chemical derivatization, as well as the introduction of additives such as plasticizers, stabilizers, fillers, processing aids, and colorants, a huge variety of plastics with different physical characteristics (e.g., melting point, density, shelf life, biodegradability, UV resistance, transparency, thermoplastic versus thermosetting plastic) can be produced. Consequently, it is not possible to provide a generic set of characteristics for each plastic class. Instead, examples of different plastics with the specified characteristics have been referenced to guide the reader to publications that provide more detailed information on any chosen subject. Degradability in water, soil, and industrial composting systems (the most controlled form of bioplastic degradation in terms of temperature, humidity, and microbial blends) has also been summarized (Figure 1). The most detailed guidelines on bioplastic degradation have been developed for industrial composting systems and these define the time required for degradation, the percentage of CO_2 emitted from the bioplastic, and any toxic residues remaining (Figure 2).

Development'. These goals include Good Health and Well-Being, Clean Water and Sanitation, Affordable and Clean Energy, Decent Work and Economic Growth, Industry, Innovation and Infrastructure, Sustainable Cities and Communities, Responsible Consumption and Production, Climate Action, Life below Water, and Life on Land.

Bioplastics include both nondegradable and **biodegradable plastics**. Both are important for sustainable solutions.

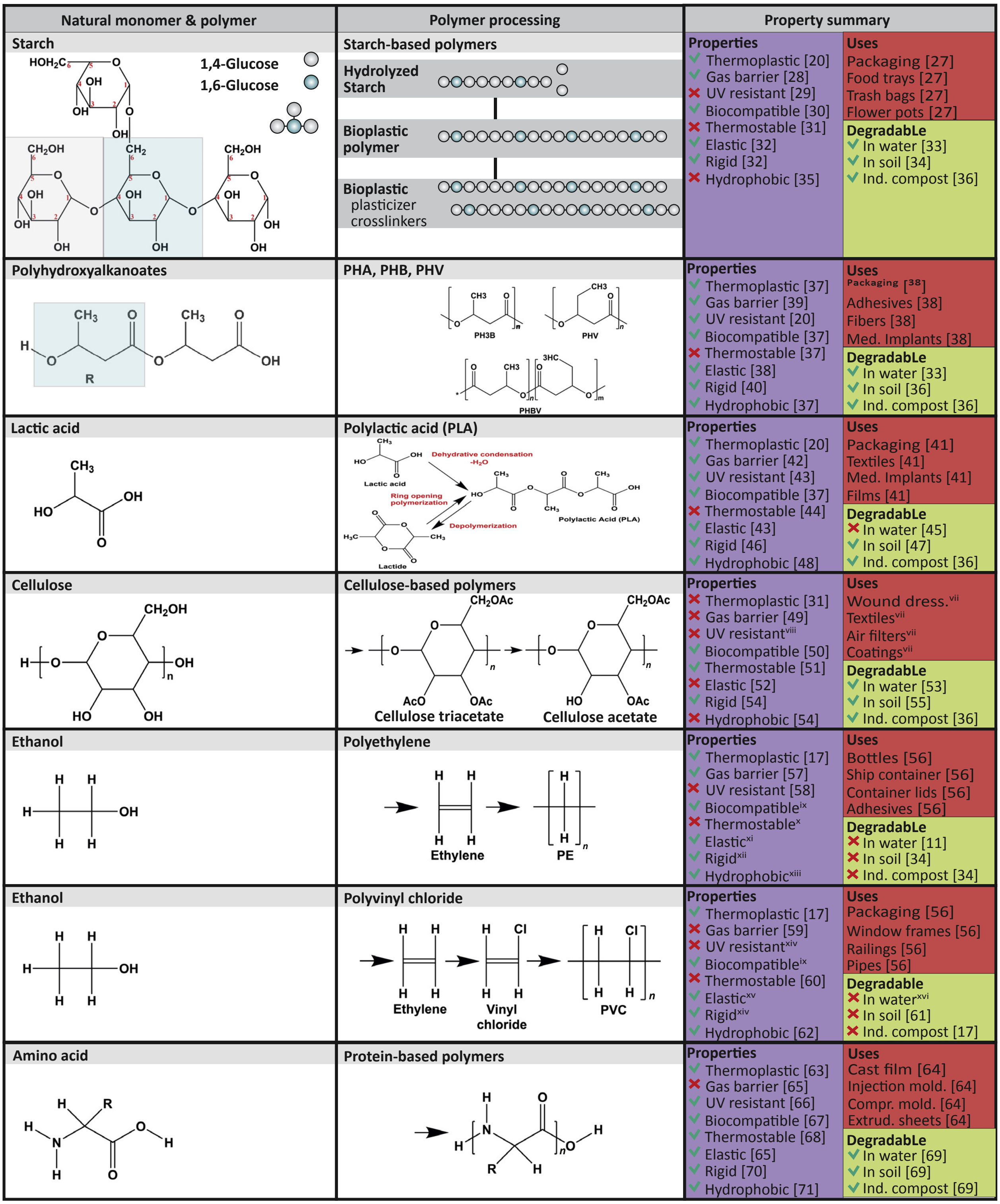
Nondegradable Bioplastics as Carbon Sinks

Nondegradable bioplastics are expected to play an increasingly important role in the development of more sustainable infrastructure (e.g., plastic-based municipal water, sewer piping, building and roofing materials, and road surfaces) that provide expanding long-term carbon sinks to support urgently needed CO_2 emissions reductions [12]. The exchange of petrochemical-based feedstocks with available 'drop-in' bio-derived replacements – for example, bio-based polyethylene (bio-PE) [17] – could enable this transition. This process would be expedited through legislated accreditation making such infrastructure eligible for carbon credits.

Biodegradable Plastics and Biodegradability Standards

In parallel, degradable bioplastics can be used to produce CO_2 neutral, short-to-medium shelf-life products that degrade fully to minimize their environmental impact. The timescale over which plastics degrade can theoretically be tailored to the product purpose. Here too, legislated national and international standards are critical, both to guide this bioplastic design process and to the sustainable development of an emerging bioplastics industry.

The legislative process has begun with the development of standards for tightly controlled industrial composting systems (Figure 2A), but due consideration must also be given to the degradation of bioplastics in home composting as well as in terrestrial and aquatic



Trends in Plant Science

(See figure legend on the bottom of the next page.)

environments to tackle widespread environmental degradation. Specifically, it is important to advance plastics that can be fully degraded to CO_2 and water in industrial composters, terrestrial, and aquatic systems and that do not release toxic byproducts (Figure 2B).

A good example of the optimization that can be achieved using bioplastics is given by the food packaging industry. Petrochemically produced plastic food packaging such as soft-drink bottles, food containers, and food trays made from polyethylene terephthalate (PET) has already been shown to persist in the environment for over 90 years (Table 1) [18,19] and this is likely to increase significantly, as longer time-series data are collected. Although steadily increasing, the global plastic recycling rate is still only around 20% [4] and exacerbates this situation. Furthermore, degradation is often only partial and in many cases leads to harmful products such as microplastics and toxic constituents [10]. Theoretically, bio-based plastic formulations can be controlled to deliver products with fit-for-purpose shelf life. For example, plastic water bottles could be designed to have a 2–5-year shelf life and to degrade under specific conditions (Figure 2). Considering that over half of the global biodegradable plastic demand is for packaging materials [20], such packaging could yield significant benefits in the future. Nevertheless, for a competitive bioplastics market, advancements in biotechnology and processing techniques are paramount to improve performance and reduce cost of bioplastics. To guide such developments, typical market prices for common bioplastics inputs and polymers are provided in Table 2.

The Advancement of the Bioplastics Industry

The bioplastics industry has been undergoing a staged development, briefly summarized in the following subsections.

Phase 1

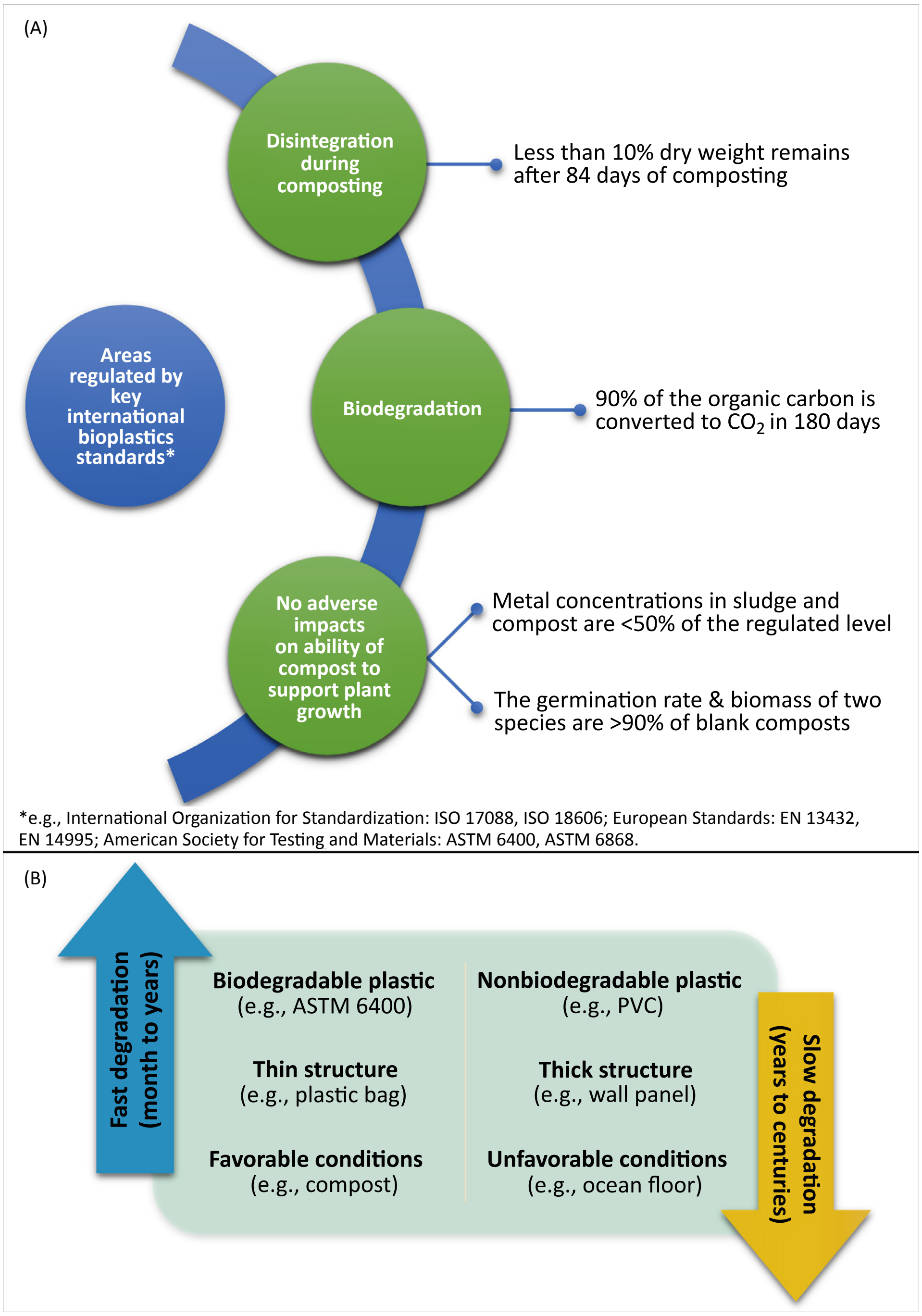
An early focus of the bioplastics industry was to increase sustainability by replacing petrochemical feedstocks with plant-based monomers and polymer inputs; these were used to demonstrate robust economic bioplastic production processes and the delivery of market-ready products (Table 1). Most bioplastics produced in this phase (e.g., starch- and cellulose-based plastics) originated from plant materials (e.g., crop residues) and were mixed into petrochemical/bioplastic blends for commercial production (Figure 1). In some cases, these were marketed as having improved biodegradability characteristics. However, due to a lack of detailed regulation, the concern remained that some of these blends do not fully degrade into CO_2 and water, but instead only partially degrade into microplastics and other harmful chemicals that can persist in the environment.

Phase 2

Proof of concept that bio-based monomers and polymers could deliver market plastics provided a solid basis to begin addressing the main limitations of petrochemically produced plastics: petrochemical dependence–associated CO_2 emissions and the rapid and long-term environmental accumulation of harmful plastics and their byproducts, including microplastics, due to poor biodegradability and toxic metals. The parallel development of new routes of

Figure 1. Major Bioplastic Classes. Starch-based polymers, polyhydroxyalkanoates (PHAs) [including polyhydroxybutyrate (PHB), polyhydroxyvalerate (PHV), poly (3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV)], polylactic acid (PLA), cellulose-based polymers, polyethylene (PE), polyvinyl chloride (PVC), and protein-based polymers. Bioplastic input monomers and polymers (left-hand column), polymer production steps (middle column), properties, uses, and degradability characteristics (right-hand columns). The natural monomer and polymer feedstocks can in most cases be derived from higher plant, microalgae, and cyanobacterial systems. Abbreviations: Compr. mold., compression molding; Extrud. sheets, extruded sheets; Ind. compost, industrial compost; injection mold., injection molding; Med. implants, medical implants; wound dress., wound dressing. See also [11,17,20,27–71] and Resources[vii–xvi].

CellPress
REVIEWS



Trends in Plant Science

Figure 2. Degradation of Bioplastics (A) Summary of key international standards for bioplastic degradability certifications[xvii,xviii] [72,73] and (B) polymer breakdown mechanisms; modified from[xix]. The current regulatory frameworks categorize the biodegradability of a product rather than its constituent resin. This is of particular importance for the degradation of composite materials consisting of multiple bioplastics. The international standards shown in Figure 2A have almost identical requirements. The information in the figure is based on ASTM 6400-12 [72]. See also Resources[xxvi–xli].

Table 1. Conventional Plastics and Their Properties[a]

Resin code	Estimated market size and unit price (2017)[b]	Uses[xx]	Degradation in wet soil (years)	Sample starch substitute	Sample PHA substitute	Sample PLA substitute	Refs
#1 PET $(C_{10}H_8O_4)n$	EUR 34.7 bn[xxi,xxii] EUR 1.05/kg[xxii]	Soft-drink bottles, food containers, trays, films	27–93	Flexible packaging	Films	Short shelf life bottle	[17–19,74]
#2 HDPE $(C_2H_4)n$	EUR 124.6 bn[xxii,xxiii] EUR 1.21/kg[xxii]	Bottles (i.e., detergents), bags, shipping containers	<700	Flexible packaging	Packaging	Shampoo bottle	[17,74–76]
#3 PVC $(C_2H_3Cl)n$	EUR 50.6–76.4 bn[xxiv,xxv] EUR 1.59/kg[xxv]	Pipes, window frames, railings, medical products	<32	Packaging film	Vinyl flooring[xxvi]	Shrink films[xxvii]	[61,77]
#4 LDPE $(C_2H_4)n$	EUR 52.5 bn[xxii,xxviii] EUR 1.12/kg[xxii]	Toys, squeezable bottles, adhesives, stretch wraps	>32	Packaging	Packaging	Coating	[61,76,78,79]
#5 PP $(C_3H_6)n$	EUR 61.4 bn[xxix,xxx] EUR 0.90/kg[xxix]	Containers, bottles (i. e., syrups), durable plastics	<100[xxxi]	Packaging	Packaging	Yogurt container	[76,80,81]
#6 PS $(C_8H_8)n$	EUR 3.93 bn[xxxii,xxxiii] EUR 0.57/kg[xxxiii]	Containers, toys, medical products, insulation	<32	Loose fill material	Medical scaffold	Insulation	[61,74,82,83]
#7 Others	Varies	Acrylic, nylon, Teflon, polycarbonate (PC)	Varies	Poly(methyl methacrylate) replacement (acrylic)	Polybutylene adipate terephthalate replacement	PC replacement	[84–86]

[a]Plastic resins have been divided into seven classes. Class 1: Polyethylene terephthalate (PET); Class 2: High-density polyethylene (HDPE); Class 3: Polyvinyl chloride (PVC); Class 4: Low-density polyethylene (LDPE); Class 5: Polypropylene (PP); Class 6: Polystyrene (PS); and Class 7: Other plastics (e.g., acrylic, nylon, polycarbonate, and Teflon). For each class, generic chemical formulae, estimated global market sizes and product values (EUR/kg), uses, and degradation characteristics are summarized. In addition, available references for bioplastics (e.g., starch-based bioplastic, PHA, and PLA) that have been substituted for, or blended with, each of these classes are provided. These fossil-based polymers are mainly nondegradable in nature.
[b]Conversion factor: USD/EUR = 0.86.

bioplastic production based on a much broader range of chemistry (Figure 1) now opened up the opportunity to expand, diversify, and scale-up the production of new bioplastics with similar or superior physical properties to petrochemical-based plastics (Table 1). This diversity also opens up the opportunity to develop new plastic blends with properties superior to the pure plastic types (detailed in Figure 1) to deliver the necessary physical and chemical characteristics

Table 2. Bioplastics and Raw Material Prices (2018)[a]

Bioplastic	Approximate price (EUR/kg)[b]
Corn starch	0.34
Ethanol	0.39
Lactic acid	1.14
Unbleached dissolving pulp	1.26
Soybean protein isolate	2.02
PLA	1.72
PHA	2.49
Cellulose acetate	21.50

[a]Prices are sourced from[xxxiv], except for ethanol[xxxv].
[b]Conversion factor: USD/EUR = 0.86.

(e.g., UV resistance, biocompatibility) for market-ready 100% bioplastic products. For example, high-value films and materials can be developed for biomedical applications and specialist bio-based feedstocks (Figure 1) synthesized to deliver enhanced polymers for 3D printing and '4D' (shape changing) products.

Phase 3

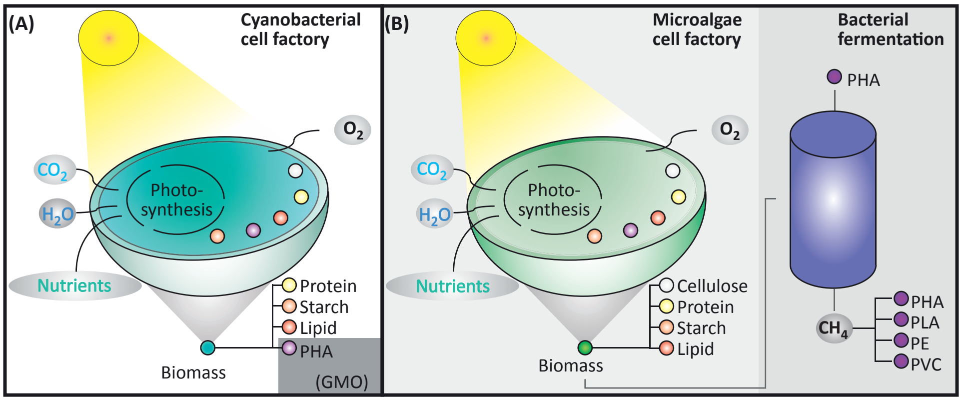
The aforementioned advances are now resulting in an expansion of the bioplastics industry[iv] and this in turn is increasing the industries' requirement for plant biomass–derived feedstocks. In the early stages of this industry expansion, it is expected that significant amounts of waste material such as crop residues can reasonably supply demand. However, as bioplastic demand expands, the increased channeling of carbon-based molecules out of agriculture and forestry could interfere with natural carbon cycles that replenish soil carbon and insure ongoing soil fertility. Consequently, next-generation microalgae and cyanobacteria systems, which are more compatible with a scaling circular bioeconomy, are beginning to be developed. Besides contributing to CO_2 capture (in long-term infrastructure) and recycling (via biodegradable plastics), microalgae and cyanobacteria systems offer the advantages that they can be located on nonarable land (expanding photosynthetic capacity), and use waste and salt water (conserving fresh water). The theoretical area of land required to supply global plastic production[iv] is calculated to be approximately 145 000 km^2, or 0.028% of the Earth's surface area (approximately 510 000 000 km^2), based on the following estimates: 1:1 mass conversion from microalgae oil to plastics, 90% conversion efficiency, 0.388 km^2 per million liters of microalgae oil (J. Roles *et al*., unpublished), and an oil density of 0.84 kg/l.

Biomass-to-Methane

>Photosynthesis performed by plants, cyanobacteria (Figure 3A), and microalgae (Figure 3B) essentially drives solar-powered reduction of CO_2, and ultimately yields a complex set of biomolecules that collectively form biomass. Perhaps the simplest way to connect this biomass feedstock into the existing petrochemical-based plastics industry is to convert it to methane through fermentation (Figure 3B). This is because a wide range of proven chemistries are already in place to convert methane into the input feedstocks for bioplastics production (Figure 1). Indeed, methane can be used to produce PHAs [21], lactic acid[v] (the precursor to PLA), ethanol (precursor to bio-PE and bio-PVC) [22], and proteins[vi] (precursor to protein-based polymers). This approach has the advantage that it minimizes both capital and operational costs, as biomass production and subsequent fermentation are relatively simple low-cost processes. Its disadvantage is that much of the solar energy used and value gained during the generation of this complex set of biomolecules are lost during its conversion back to methane, from which different bioplastic precursor molecules must be resynthesized. Nevertheless, it provides a simple and effective way to start up renewable bioplastics production and could evolve into an intermediate approach in which complex biomolecules are converted to longer-chain fractions with reduced energetic losses (e.g., light naphtha, C3–C5 molecules).

Biorefinery Approach

An alternative strategy is to separate biomass into its biomolecular components using a biorefinery approach (Figure 3). Processes based on mechanical cell cracking and hydrothermal liquefaction are being developed [23] to disrupt cells and gently release the constituent proteins, lipids, carbohydrates, nucleic acids, and where available, cellulose or other valuable cell wall materials. These constituents can then be used as inputs to produce the wide range of bioplastic classes (Figure 1). Critical to the success of this



Trends in Plant Science

Figure 3. (A) Cyanobacterial and (B) Microalgae-Based Solar-Driven Bioplastics Production Routes
For a Figure360 Author Presentation of Figure 3, see the figure legend at https://doi.org/10.1016/j.tplants.2018.11.010
Abbreviations: GMO, genetically modified organism; PE, polyethylene; PHA, polyhydroxyalkanoate; PLA, polylactic acid; PVC, polyvinyl chloride.

approach will be the ability to achieve cost benefit, despite a relatively high capital cost required to fractionate the biomass into its constituent components. The value from this process is expected to be realized through the establishment of co-production streams of pure product. For instance, cyanobacteria can be used as a feedstock for the co-production of polyhydroxybutyrate (PHB), animal feed, pigments, methane, and fertilizers [24]. In another study, Kwan *et al*. [25] performed a technoeconomic study on a biorefinery design for food waste valorization through fungal hydrolysis and microalgae cultivation, which ultimately leads to the production of plasticizer, lactic acid, and animal feed. Economic feasibility was only achieved when the production was focused on plasticizer and lactic acid, which are high-value products [25]. The production of multiple bioplastics from the same biomass source is central to these strategies as it helps to offset the relatively high capital cost required for its fractionation and purification. Detailed technoeconomic and life-cycle modeling tools are being developed to fast-track biorefinery systems optimization, the development of robust business models, and to de-risk scale up. Through such modeling approaches it is possible to identify the most and least valuable production streams, the capital and operational costs associated with these, and to configure biorefinery processes that deliver good economic (e.g., profitability), social (e.g., energy efficiency), and environmental (e.g., greenhouse gas emissions) outcomes.

Genetically Modified Organism Production Cell Lines

Genetically modified cyanobacteria can already directly use solar energy to drive enhanced PHA production (Figure 3A, dark shading) and it is expected that with advances in clustered regularly interspaced short palindromic repeats (CRISPR) technologies microalgae will also increasingly be engineered to optimize light capture efficiency and specific biochemical pathways [26]. The genetic engineering of specific pathways can of course enable the production of novel precursor molecules to confer a broad range of physical and chemical properties to next-generation bioplastics. The use of genetically modified organisms (GMOs) therefore can improve both process efficiency and cost. Furthermore, in contrast to crop-based production, microalgae and cyanobacterial GMOs can be produced in closed systems, in which they can be effectively destroyed during the production process.

Concluding Remarks

As our global population and its living standards are forecast to increase, so is the demand for plastic products from packaging to high-value medical devices (Table 1, Figure 1). Reduction in plastic use is an option but internationally has proven difficult to regulate. Solar-driven photosynthetic processes (Figure 3) offer important new routes for the production of sustainable bioplastics used for both CO_2 neutral biodegradable products and bioplastic-based infrastructure that can act as long-term carbon sinks. To drive sustainable industry development, it will be essential not only to regulate for the ability of bioplastics to degrade (e.g., to microplastics and environmentally compromising products), but for them to degrade fully to CO_2 and water without the release of harmful residual chemicals. Figure 2 highlights the main bioplastics standards currently in operation. The expanding capabilities of CRISPR-based genetic engineering open up the opportunity to increase process efficiency, as well as precursor diversity and quality. It will ultimately help to fast-track the realization of high-value opportunities. The production of low-value products from bioplastics is a long-term challenge, which will likely be addressed as systems develop down the cost curve. Currently, the production of microalgae biomass is estimated to cost around EUR 0.6–1 kg^{-1} dry weight. Given that most of the plastic prices (Table 1) are currently around EUR 1 kg^{-1}, initially specialist higher-value bioplastics will likely be targeted (e.g., for biomedical devices), while production costs are driven down through innovation, especially if externalities are not included. The inclusion of externality costs, which include the cost of recycling plastic, environmental degradation, and health-related costs, require improved regulation, which if enacted could significantly increase the speed of transition to a more renewable circular bioeconomy based on bioplastics.

Outstanding Questions

What are short- and long-term impacts of microplastics on human health?

How can we accurately calculate and compare life-cycle impacts of conventional and bio-based plastics?

What are the strategies that can be deployed to make microalgal bioplastics biorefineries economically feasible?

Is it possible to design polymers including their additives, which will ultimately degrade fully into H_2O and CO_2?

How can biodegradation be halted or accelerated in the nature?

How can biodegradability standards be improved to cover a wide range of degradation environments?

Is it possible to standardize degradation speed and methods (such as the utilization of defined microorganisms)?

How can bioplastics best be developed as effective carbon sinks?

How can policies be best designed to improve the bioplastics sector?

Acknowledgments

H.K. thanks the University of Queensland for his PhD scholarship. C.F. is grateful to the Wenner-Gren Foundation, Umeå University, and the NordForsk NCoE programme 'NordAqua' (project number 82845) for allowing her to perform a sabbatical visit in B.H.'s group. B.H. thanks the ARC for financial support (LP150101147).

Resources

[i] https://www.cia.gov/library/publications/the-world-factbook/geos/xx.html
[ii] https://repository.library.noaa.gov/view/noaa/2509
[iii] https://www.un.org/sustainabledevelopment/sustainable-development-goals/
[iv] https://docs.european-bioplastics.org/publications/market_data/2017/Report_Bioplastics_Market_Data_2017.pdf
[v] https://www.sciencedirect.com/science/article/pii/S1351418016304615
[vi] http://www.unibio.dk/technology/introduction
[vii] http://www.nollaantimicrobial.com/industrial/cellulosic-fibers
[viii] http://polymerdatabase.com/Films/Plastic%20Films3.html
[ix] https://www.zeusinc.com/wp-content/uploads/2014/03/RESINATE-SE-Biocompatibility-of-Plastics.pdf
[x] http://www.appstate.edu/~clementsjs/polymerproperties/zeus_thermal_degradation.pdf
[xi] https://www.awwa.org/Portals/0/files/publications/documents/M55LookInside.pdf
[xii] https://www.dow.com/polyethylene/na/en/application/rigid/bottle.htm
[xiii] https://ieeexplore.ieee.org/document/641090
[xiv] http://polymerdatabase.com/polymer%20classes/Polychloroolefin%20type.html
[xv] https://omnexus.specialchem.com/product-categories/tpes-tpvs-pvc-elastomer
[xvi] http://www.ipexna.com/media/2086/pvc-chemical-resistance-guide.pdf
[xvii] http://www.organics-recycling.org.uk/uploads/article1983/Concise%20guide%20to%20Compostable%20Products%20and%20Packaging.pdf
[xviii] http://www.biobasedeconomy.eu/app/uploads/sites/2/2017/03/Report-on-current-relevant-biodegradation-and-ecotoxicity-standards.pdf
[xix] https://www.pce.parliament.nz/media/196468/pce-infographic-2-web.jpg
[xx] https://plastics.americanchemistry.com/Plastic-Resin-Codes-PDF/
[xxi] https://www.plasticsinsight.com/resin-intelligence/resin-prices/polyethylene-terephthalate/

[xxii]https://www.plasticportal.eu/en/en/ceny-polymerov/lm/1/

[xxiii]https://www.plasticsinsight.com/resin-intelligence/resin-prices/hdpe/

[xxiv]https://www.marketsandmarkets.com/PressReleases/polyvinyl-chloride.asp

[xxv]https://www.plasticsinsight.com/resin-intelligence/resin-prices/pvc/

[xxvi]https://www.sciencedirect.com/science/article/pii/S0306374716300185

[xxvii]http://www.weforyou.pro/en/about-pla/

[xxviii]https://www.statista.com/statistics/682105/global-polyethylene-production-forecast-by-region/

[xxix]https://www.icis.com/chemicals/polypropylene/

[xxx]https://www.sk.kz/upload/iblock/713/713c4a54b6fdb2183807bba0dc84cbb3.pdf

[xxxi]https://plasticpipe.org/pdf/tepffa-european-plastic-pipe-fittings-association.pdf

[xxxii]https://www.grandviewresearch.com/industry-analysis/expanded-polystyrene-eps-market

[xxxiii]http://www.plasticsnewseurope.com/article/20170301/PNE/170309995/polystyrene-prices-soar-to-an-all-time-high

[xxxiv]https://www.alibaba.com/

[xxxv]https://markets.businessinsider.com/commodities/ethanol-price

[xxxvi]https://www.iso.org/standard/57901.html

[xxxvii]https://www.iso.org/standard/55874.html

[xxxviii]https://www.en-standard.eu/din-en-13432-requirements-for-packaging-recoverable-through-composting-and-biodegradation-test-scheme-and-evaluation-criteria-for-the-final-acceptance-of-packaging-english-version-of-din-en-13432/

[xxxix]https://www.en-standard.eu/din-en-14995-plastics-evaluation-of-compostability-test-scheme-and-specifications/

[xl]https://www.astm.org/Standards/D6400.htm

[xli]https://www.astm.org/Standards/D6868.htm

Supplemental Information

Supplemental information associated with this article can be found online at https://doi.org/10.1016/j.tplants.2018.11.010.

References

1. Hall, C.A. *et al.* (2014) EROI of different fuels and the implications for society. *Energy Policy* 64, 141–152
2. BP (2018) *Statistical Review of World Energy.* (67th edn.), BP https://www.bp.com/content/dam/bp/en/corporate/pdf/energy-economics/statistical-review/bp-stats-review-2018-full-report.pdf
3. Harmsen, P.F. *et al.* (2014) Green building blocks for bio-based plastics. *Biofuels, Bioprod. Biorefin.* 8, 306–324
4. Geyer, R. *et al.* (2017) Production, use, and fate of all plastics ever made. *Sci. Adv.* 3, e1700782
5. Wagner, L. *et al.* (2016) Trading off global fuel supply, CO_2 emissions and sustainable development. *PLoS One* 11, e0149406
6. Lebreton, L. *et al.* (2018) Evidence that the Great Pacific Garbage Patch is rapidly accumulating plastic. *Sci. Rep.* 8, 4666
7. Van Sebille, E. (2015) The oceans' accumulating plastic garbage. *Phys.Today* 68, 60
8. Eriksen, M. *et al.* (2014) Plastic pollution in the world's oceans: more than 5 trillion plastic pieces weighing over 250,000 tons afloat at sea. *PLoS One* 9, e111913
9. Barboza, L.G.A. *et al.* (2018) Marine microplastic debris: an emerging issue for food security, food safety and human health. *Mar. Pollut. Bull.* 133, 336–348
10. Wright, S.L. and Kelly, F.J. (2017) Plastic and human health: a micro issue? *Environ. Sci. Technol.* 51, 6634–6647
11. Rutkowska, M. *et al.* (2002) Biodegradability of polyethylene starch blends in sea water. *Pol. Int. J. Environ. Stud.* 11, 267–272
12. Carus, M. and Dammer, L. (2013) Food or non-food: which agricultural feedstocks are best for industrial uses? *Ind. Biotechnol.* 9, 171–176
13. CIEL (2017) How fracked gas, cheap oil, and unburnable coal are driving the plastics boom. In *Fueling Plastics*, pp. 1–9, Center for International Environment Law
14. CIEL (2017) Fossils, plastics, & petrochemical feedstocks. In *Fueling Plastics*, pp. 1–5, Center for International Environment Law
15. Brooks, A.L. *et al.* (2018) The Chinese import ban and its impact on global plastic waste trade. *Sci. Adv.* 4, eaat0131
16. Bastos Lima, M.G. (2018) Toward multipurpose agriculture: food, fuels, flex crops, and prospects for a bioeconomy. *Global Environ. Politics* 18, 143–150
17. Delft, C.E. (2017) *Biobased Plastics in a Circular Economy,* CE Delft
18. Edge, M. *et al.* (1991) Aspects of poly (ethylene terephthalate) degradation for archival life and environmental degradation. *Polym. Degrad. Stab.* 32, 131–153
19. Allen, N.S. *et al.* (1994) Physicochemical aspects of the environmental degradation of poly (ethylene terephthalate). *Polym. Degrad. Stab.* 43, 229–237
20. Scarfato, P. *et al.* (2015) Recent advances and migration issues in biodegradable polymers from renewable sources for food packaging. *J. Appl. Polym. Sci.* 132, 42597
21. Strong, P.J. *et al.* (2016) The opportunity for high-performance biomaterials from methane. *Microorganism* 4, 11
22. Okolie, C. *et al.* (2017) Conversion of methane into methanol and ethanol over nickel oxide on ceria–zirconia catalysts in a single reactor. *Angew. Chem. Int. Ed.* 56, 13876–13881
23. Günerken, E. *et al.* (2015) Cell disruption for microalgae biorefineries. *Biotechnol. Adv.* 33, 243–260
24. Meixner, K. *et al.* (2018) Cyanobacteria biorefinery—production of poly (3-hydroxybutyrate) with *Synechocystis salina* and utilisation of residual biomass. *J. Biotechnol.* 265, 46–53
25. Kwan, T.H. *et al.* (2015) Techno-economic analysis of a food waste valorization process via microalgae cultivation and co-production of plasticizer, lactic acid and animal feed from algal biomass and food waste. *Bioresour. Technol.* 198, 292–299

26. Ringsmuth, A.K. *et al.* (2016) Can photosynthesis enable a global transition from fossil fuels to solar fuels, to mitigate climate change and fuel-supply limitations? *Renew. Sustain. Energy Rev.* 62, 134–163
27. Lörcks, J. (1998) Properties and applications of compostable starch-based plastic material. *Polym. Degrad. Stab.* 59, 245–249
28. Ashok, A. *et al.* (2016) Biodegradable polymers for sustainable packaging applications: a review. *IJBB* 1, 11
29. Vasile, C. and Seymour, R.B. (2000) *Handbook of Polyolefins,* Marcel Dekker
30. Marques, A. *et al.* (2002) The biocompatibility of novel starch-based polymers and composites: *in vitro* studies. *Biomaterials* 23, 1471–1478
31. Peelman, N. *et al.* (2015) Heat resistance of new biobased polymeric materials, focusing on starch, cellulose, PLA, and PHA. *J. Appl. Polym. Sci.* 132, 42305
32. Martin, O. and Averous, L. (2001) Poly (lactic acid): plasticization and properties of biodegradable multiphase systems. *Polymer* 42, 6209–6219
33. Imam, S. *et al.* (1999) Degradation of starch–poly (β-hydroxybutyrate-co-β-hydroxyvalerate) bioplastic in tropical coastal waters. *Appl. Environ. Microbiol.* 65, 431–437
34. Gómez, E.F. and Michel, F.C., Jr (2013) Biodegradability of conventional and bio-based plastics and natural fiber composites during composting, anaerobic digestion and long-term soil incubation. *Polym. Degrad. Stab.* 98, 2583–2591
35. Lopez-Gil, A. *et al.* (2014) Strategies to improve the mechanical properties of starch-based materials: plasticization and natural fibers reinforcement. *Polímeros* 24, 36–42
36. Emadian, S.M. *et al.* (2017) Biodegradation of bioplastics in natural environments. *Waste Manag.* 59, 526–536
37. Li, Z. *et al.* (2016) Polyhydroxyalkanoates: opening doors for a sustainable future. *NPG Asia Mater.* 8, e265
38. Chen, G.-Q. (2009) A microbial polyhydroxyalkanoates (PHA) based bio- and materials industry. *Chem. Soc. Rev.* 38, 2434–2446
39. Bartkowiak, A. *et al.* (2016) Innovations in food packaging materials. In *Emerging and Traditional Technologies for Safe, Healthy and Quality Food*, pp. 383–412, Springer
40. Singh, M. *et al.* (2015) Challenges and opportunities for customizing polyhydroxyalkanoates. *Indian J. Microbiol.* 55, 235–249
41. Castro-Aguirre, E. *et al.* (2016) Poly (lactic acid)—mass production, processing, industrial applications, and end of life. *Adv. Drug Deliv. Rev.* 107, 333–366
42. Carosio, F. *et al.* (2014) Efficient gas and water vapor barrier properties of thin poly (lactic acid) packaging films: functionalization with moisture resistant Nafion and clay multilayers. *Chem. Mater.* 26, 5459–5466
43. Farrington, D. *et al.* (2005) Poly (lactic acid) fibers. In *Biodegradable and Sustainable Fibres* (Blackburn, R.S., ed.), p. 191, Elsevier
44. Araújo, A. *et al.* (2013) UV stability of poly (lactic acid) nanocomposites. *J. Mater. Sci. Eng B* 3, 75
45. Bagheri, A.R. *et al.* (2017) Fate of so-called biodegradable polymers in seawater and freshwater. *Global Challenges* 1, 1700048
46. Farah, S. *et al.* (2016) Physical and mechanical properties of PLA, and their functions in widespread applications—a comprehensive review. *Adv. Drug Deliv. Rev.* 107, 367–392
47. Weng, Y.-X. *et al.* (2013) Biodegradation behavior of poly (butylene adipate-co-terephthalate) (PBAT), poly (lactic acid) (PLA), and their blend under soil conditions. *Polym. Test.* 32, 918–926
48. Yang, G. *et al.* (2018) *Bioinspired Materials Science and Engineering,* John Wiley & Sons
49. Ach, A. (1993) Biodegradable plastics based on cellulose acetate. *J. Macromol. Sci. Part A Pure Appl. Chem.* 30, 733–740
50. Modulevsky, D.J. *et al.* (2016) Biocompatibility of subcutaneously implanted plant-derived cellulose biomaterials. *PLoS One* 11, e0157894
51. Suwantong, O. and Supaphol, P. (2015) Applications of cellulose acetate nanofiber mats. In *Handbook of Polymer Nanocomposites. Processing, Performance and Application*, pp. 355–368, Springer
52. Vesterinen, A.H. *et al.* (2010) The effect of water-soluble polymers on rheology of microfibrillar cellulose suspension and dynamic mechanical properties of paper sheet. *J. Appl. Polym. Sci.* 116, 2990–2997
53. Hofsten, B.V. and Edberg, N. (1972) Estimating the rate of degradation of cellulose fibers in water. *Oikos* 23, 29–34
54. Wang, Z. *et al.* (2014) Synthesis and characterization of designed cellulose-graft-polyisoprene copolymers. *Polym. Chem.* 5, 3379–3388
55. Zhang, L. *et al.* (1996) Biodegradability of regenerated cellulose films in soil. *Ind. Eng. Chem. Res.* 35, 4682–4685
56. American Chemistry Council (n.d.) *Plastic Packaging Resins*, American Chemistry Council.
57. Mangaraj, S. *et al.* (2015) Modeling of gas transmission properties of polymeric films used for MA packaging of fruits. *J. Food Sci. Technol.* 52, 5456–5469
58. Martínez-Romo, A. *et al.* (2015) Effect of ultraviolet radiation in the photo-oxidation of high density polyethylene and biodegradable polyethylene films. *J. Phys. Conf. Ser.* 582, 012026
59. Coles, R. *et al.* (2003) *Food Packaging Technology,* CRC Press
60. Braun, D. *et al.* (1990) Thermal degradation of poly (vinyl chloride) blends. *Angew. Makromol. Chem.* 181, 23–40
61. Otake, Y. *et al.* (1995) Biodegradation of low-density polyethylene, polystyrene, polyvinyl chloride, and urea formaldehyde resin buried under soil for over 32 years. *J. Appl. Polym. Sci.* 56, 1789–1796
62. Asadinezhad, A. *et al.* (2012) Recent progress in surface modification of polyvinyl chloride. *Materials* 5, 2937–2959
63. Vaz, C. *et al.* (2003) Casein and soybean protein-based thermoplastics and composites as alternative biodegradable polymers for biomedical applications. *J. Biomed. Mater. Res. Part A* 65, 60–70
64. Bier, J.M. *et al.* (2014) Thermal transitions and structural relaxations in protein-based thermoplastics. *Macromol. Mater. Eng.* 299, 524–539
65. Guilbert, S. *et al.* (2006) Protein-based plastics and composites as smart green materials. In *ACS Symposium Series*, pp. 334–350, Oxford University Press
66. Sionkowska, A. (2006) The influence of UV light on collagen/poly (ethylene glycol) blends. *Polym. Degrad. Stab.* 91, 305–312
67. Urry, D.W. (2007) *What Sustains Life?: Consilient Mechanisms for Protein-Based Machines and Materials.* Springer Science & Business Media
68. Gómez-Heincke, D. *et al.* (2017) Improvement of mechanical and water absorption properties of plant protein based bioplastics. *Food Hydrocolloids* 73, 21–29
69. Spence, K.E. *et al.* (1996) Soil and marine biodegradation of protein—starch plastics. In *Hydrogels and Biodegradable Polymers for Bioapplications*, pp. 149–158, American Chemical Society
70. Perez-Puyana, V. *et al.* (2017) Development of pea protein-based bioplastics with antimicrobial properties. *J. Sci. Food Agric.* 97, 2671–2674
71. Jerez, A. *et al.* (2007) Protein-based bioplastics: effect of thermo-mechanical processing. *Rheol. Acta* 46, 711–720
72. ASTM (2012) *Standard Specification for Labeling of Plastics Designed to Be Aerobically Composted in Municipal or Industrial Facilities, D6400-12,* ASTM
73. ASTM (2017) *Standard Specification for Labeling of End Items That Incorporate Plastics and Polymers as Coatings or Additives with Paper and Other Substrates Designed to Be Aerobically Composted in Municipal or Industrial Facilities, D6868-17,* ASTM
74. Gross, R.A. and Kalra, B. (2002) Biodegradable polymers for the environment. *Science* 297, 803–807
75. Rowe, R. *et al.* (2009) Ageing of HDPE geomembrane exposed to air, water and leachate at different temperatures. *Geotext. Geomembr.* 27, 137–151
76. Keskin, G. *et al.* (2017) Potential of polyhydroxyalkanoate (PHA) polymers family as substitutes of petroleum based polymers for packaging applications and solutions brought by their composites to form barrier materials. *Pure Appl. Chem.* 89, 1841–1848

77. Cannarsi, M. *et al.* (2005) Use of biodegradable films for fresh cut beef steaks packaging. *Meat Sci.* 70, 259–265

78. Niaounakis, M. (2015) *Biopolymers: Applications and Trends,* William Andrew

79. Debiagi, F. *et al.* (2018) Thermoplastic starch-based blends: processing, structural, and final properties. In *Starch-Based Materials in Food Packaging*, pp. 153–186, Elsevier

80. Janssen, L. and Moscicki, L. (2006) Thermoplastic starch as packaging material. *Acta Sci. Pol. Technica Agraria* 5, 19–25

81. Petchwattana, N. and Naknaen, P. (2016) Influence of packaging material and storage time on physical, chemical and microbiological properties of set yogurt: a comparative study between modified biodegradable poly (lactic acid) and polypropylene. *J. Eng. Sci. Technol.* 11, 1437–1449

82. Zaikov, G.E. *et al.* (2017) *Natural-Based Polymers for Biomedical Applications,* Apple Academic Press

83. Parker, K. *et al.* (2011) Expanded polylactic acid-an eco-friendly alternative to polystyrene foam. *J. Cell. Plast.* 47, 233–243

84. Chiellini, E. and Solaro, R. (2012) *Biodegradable Polymers and Plastics,* Springer Science & Business Media

85. Cunha, M. *et al.* (2016) Film blowing of PHBV blends and PHBV-based multilayers for the production of biodegradable packages. *J. Appl. Polym. Sci.* 133, 42633

86. Ebnesajjad, S. (2012) *Handbook of Biopolymers and Biodegradable Plastics: Properties, Processing and Applications,* William Andrew