PHA Biodegradable Plastics Industry White Paper

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Preface

Introduction to the White Paper

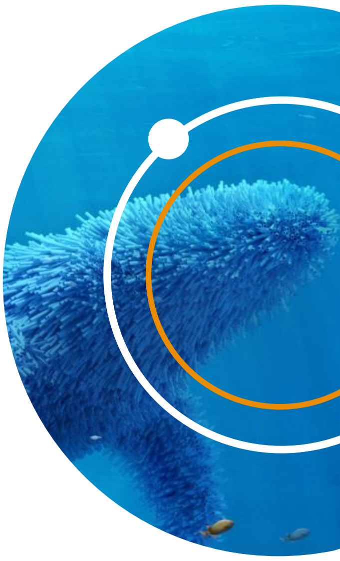
Driven by policies aimed at carbon neutrality, energy transition and environmental protection in recent years, biodegradable plastic, the optimal alternative to conventional plastics, has gained tremendous policy traction in its usage and promotion.

Polyhydroxyalkanoates (PHAs) are a class of biodegradable materials. PHAs are natural macromolecular polymers synthesized by a series of microorganisms and are biodegradable in aerobic and anaerobic conditions. As PHA mimics plastics in physical and mechanical property and processability, the bacteria-produced polymer family can take over traditional plastics given scale production capacity.

The superior degradability and physical properties of PHAs and the growing production technology readiness and ever-expanding market size significantly drive product development, making PHAs the most promising biodegradable polymers. It is expected that the PHAs market size will reach 62.9 billion RMB in the next three to five years and major markets for the polymer family are segments such as disposable packaging materials and cutlery, where recycling is difficult but much needed.

The White Paper collects input and offers insight on market macro environment, technical characteristics, industry features, industrial value chain and competitive landscape of PHA, and provides valuable references for domestic PHA sector to grasp market opportunities and achieve rapid development. The first chapter of the White Paper provides an analysis on the macro environment of PHA development and presents a summary of relevant supportive policies at home and abroad. The second chapter illustrates PHA technology characteristics, focusing on the short-term, medium-term and long-term market size and development trends of the polymer family. The third chapter provides an overview of the status quo of the PHA sector and explores a series of topics including production cost, types, applications and production challenges of the polymer. The fourth chapter elaborates the value of PHA industrial chain and concludes the value rationale of the sector by analyzing value distribution of similar industrial chains. The fifth chapter offers a benchmark analysis between the development of PHA and similar sectors and their market leaders.

Overview of Bluepha



Bluepha is dedicated to design, development, production and sales of novel bio-based molecules and materials, including marine degradable biopolymer PHA, regenerative medicine materials, new functional ingredients for cosmetics and probiotic products. Bluepha aims to facilitate business clients across various sectors to differentiate themselves in competition. These sectors include consumer goods, food, healthcare, agriculture and industrial goods.

Bluepha owns 10 PHA granted patents and sets pace in the technical field. Meanwhile, Bluepha is well prepared in capital reserve for PHA commercial effort. By January 2022, Bluepha had completed an aggregated financing amount of over 1.5 billion RMB. In addition, Bluepha's phase I PHA plant is about to complete construction, making it the first PHA project with production capacity of 5,000 tons and above in China.

Macro Environment:

Biodegradable material is the megatrend

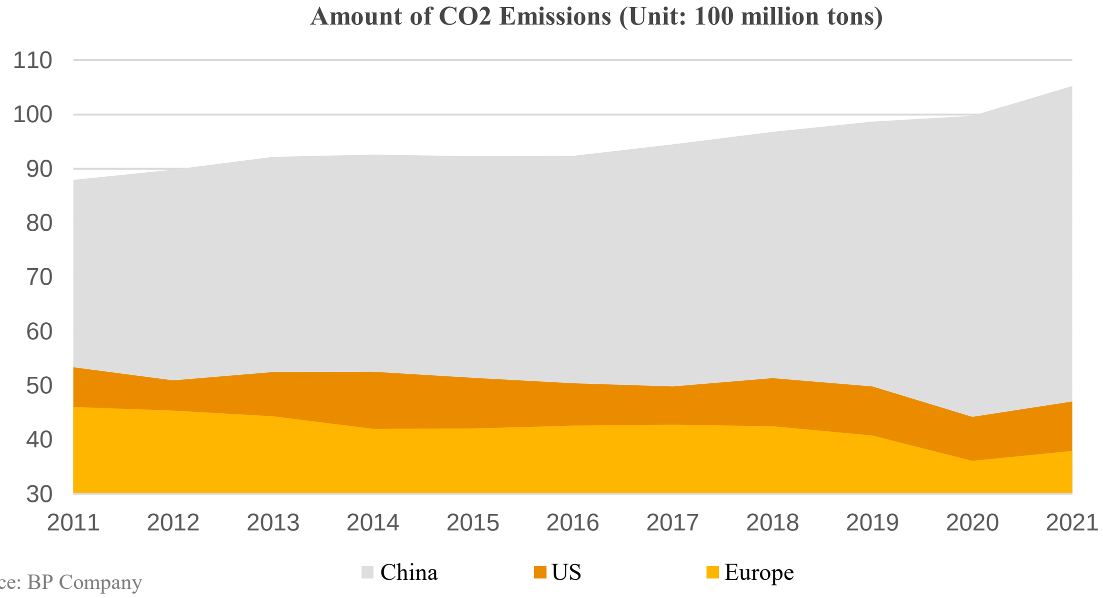
1.1 Climate risk and carbon neutrality strategy

At present, global warming becomes increasingly difficult to tackle, crisis events resulted from climate change have wrought adverse implications and posed tremendous menace to ecological environment and human society. These crises include frequent occurrence of extreme disasters, destruction of ecosystems and aggravation of socioeconomic burden. By the end of the 21st Century, the global temperature will rise by 5 degrees Celsius, grain production will reduce by half and 75% of species will face extinction if we do not go all out to deal with the issue[1]. On December 12th, 2015, 178 countries adopted the *Paris Agreement* at the 21st UN Climate Change Conference (COP21). The agreement is committed to adopting actions to cope with global climate change from the year 2020 and aims to limit the average global temperature increase to below 2 degree Celsius above pre-industrial levels. The agreement will also pursue efforts to limit the temperature increase to 1.5 degree Celsius to curb the trend of global warming. At COP26 held at Glasgow, United Kingdom in November 2021, parties assessed and summarized previous efforts on climate governance, made commitments to enhance and accelerate efforts towards emission reduction, and explored topics including carbon trading schemes and adoption of renewable energy. Up to now, 58 countries, responsible for over half of the greenhouse gas emissions worldwide, have pledged to achieve carbon neutrality by 2050.

To cope with grim situation, China put forward "Carbon Neutrality Strategy" in 2020 and elevated it to national strategy.

As a contracting party to the *Paris Agreement*, China proposed the goal of As a contracting party to Paris Agreement, China proposed the goal of "pursuing efforts to peak its carbon emissions by 2030 and reach carbon neutrality by 2060". In 2021, the government work report of the National People's Congress (NPC) and Chinese People's Political Consultative Conference (CPPCC) stated that China shall solidly carry out various works on carbon peaking and neutrality, optimize industrial structure and energy mix and formulate action plans on carbon peaking before 2030. The report kicked start the implementation of pertinent measures for carbon peaking and neutrality. In 2022, *China's Strategy and Path towards Carbon Peaking and Carbon Neutrality* offered specific details on eight strategies including non-fossil fuel alternatives strategy and carbon sequestration strategy to reach carbon peaking and neutrality. The recent report of the 20th National Congress of Communist Party of China reiterated the above concepts and accentuated that China will embark on a path to actively and steadily advance carbon peaking and neutrality agenda. China will actively engage in global governance to tackle climate change with the following endeavors: implement carbon peaking actions in an organized and phased manner on the premise of taking stock of China's domestic energy resources endowment and deepen energy revolution to accelerate the planning and construction of new energy systems.

China's carbon emission level increased by 5.8% year-on-year in 2021, lifting its global share to 31.1%[2]. As the largest developing country, there is only a time window of 30 years for China to fulfill its pledge of moving from "carbon peaking" to "carbon neutrality". Therefore, the imperatives of energy and industrial transformation is more urgent and the path towards low-carbon transition is both arduous and daunting.



Source: BP Company

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[1]《中国碳中和通用指引》， BCG

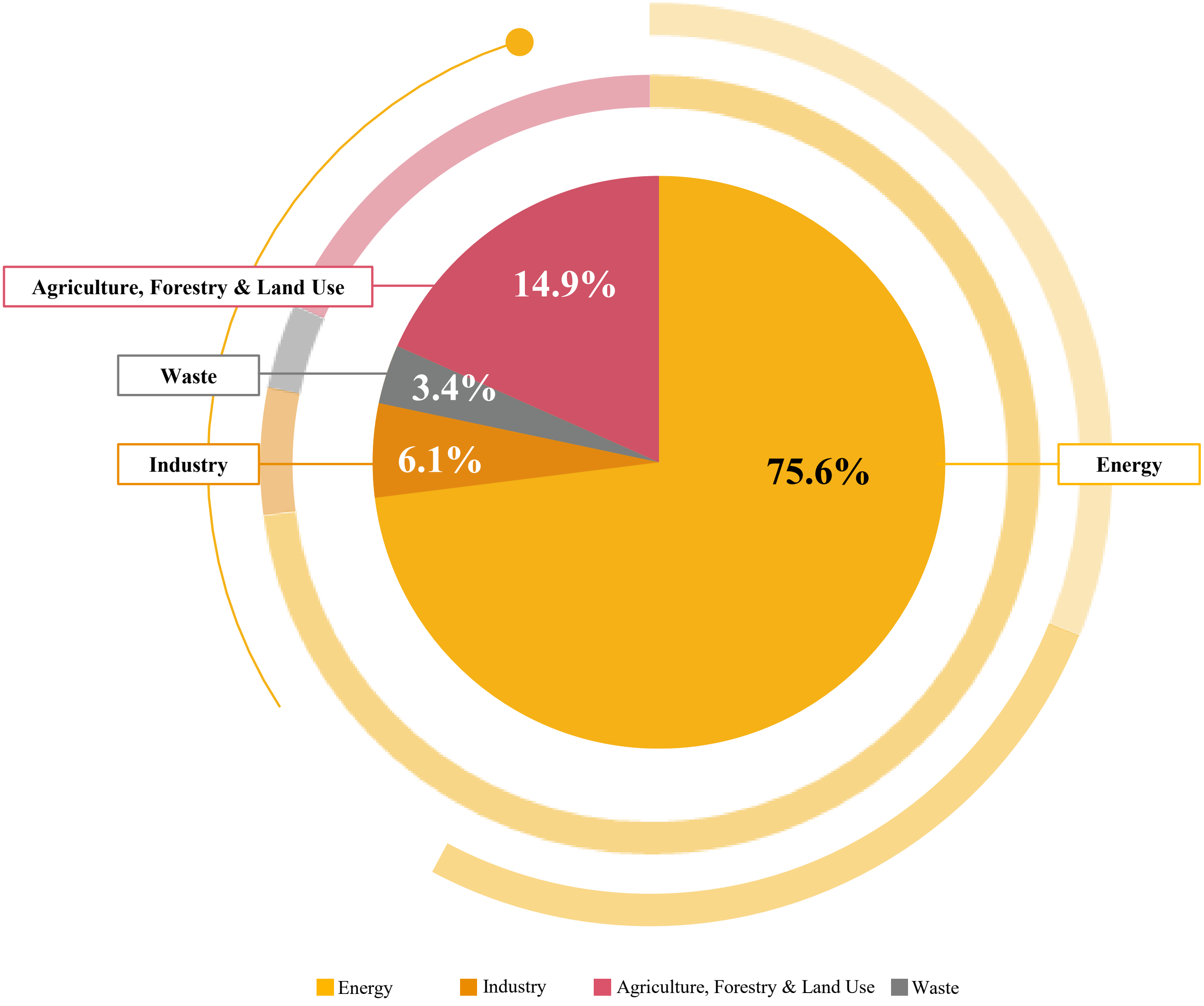
[2] *Statistical Review of World Energy 2022*

1.2 Reduce oil dependence becomes the key as “Dual Carbon Goal” unfolds

1.2.1 The current energy mix and carbon emission in the world

According to the statistics of World Resources Institute, fossil fuel is the primary source of CO2 emission in the world, taking up 75.6% of total carbon emissions[3]. *Net Zero by 2050-A Roadmap for the Global Energy Sector* suggests investment in fossil energy must be avoided if we were to achieve net zero carbon goal in 2050[4]. The *Working Guidance for Carbon Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy* printed and issued by the Central Committee of CPC and State Council in 2021 pointed out that the share of non-fossil energy consumption shall reach around 25% by 2030 and be over 80% by 2060[5].

Percentage of global greenhouse gas emissions by sector (%)



Source: World Resources Institute

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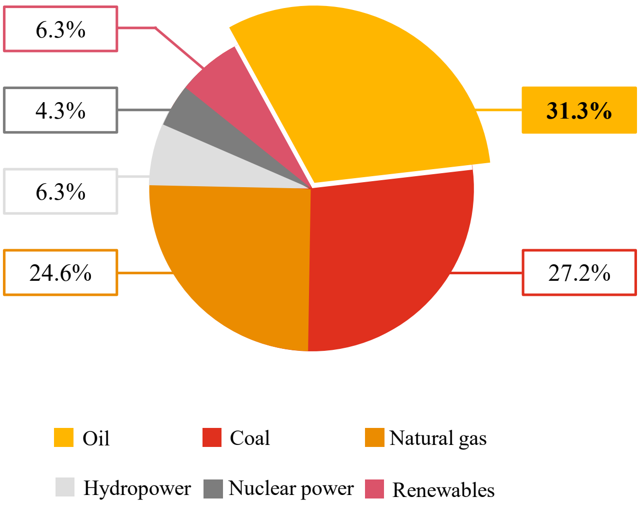
[3] World Resources Institute

[4] *Net Zero by 2050-A Roadmap for the Global Energy Sector*, IEA

[5]《中共中央国务院关于完整准确全面贯彻新发展理念做好碳达峰碳中和工作的意见》， 中国政府网

The consumption of oil, an important part of fossil energy, ranked first among the global energy consumption mix in 2021, reaching 31.3%[2]. China’s daily oil consumption had moved from 14.41 million barrels in 2020 to 15.44 million barrels in 2021, responsible for 20% of the increase in global oil consumption. This means curtailing consumption of fossil fuels like oil is crucial to reduction of greenhouse gas emissions in China.

Percentage of global energy consumption structure (%)



Source: BP Company

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[6]《中国能源大数据报告（2022）》， 中能传媒研究院

1.2.2 Emerging manufacturing sectors mushroomed in the wake of carbon neutrality strategy have equipped us with new toolkit against climate change

1.2.2.1 Reducing industry’s oil dependence through the lens of “new energy”

New energy vehicles (NEVs) industry: Since 95% of the energy required by the global transportation sector comes from oil, relevant polices to reduce the use of fuel vehicles have been vigorously introduced in many countries and regions. For instance, United Kingdom has announced a total ban on the sales of fuel vehicles from 2030, and European Union and California, US will ban the sales of fuel vehicles from 2035. Major carmakers also have explicitly stated to discontinue sales of fuel vehicles. Six automakers including Volvo, Ford and Mercedes have pledged to do just so before 2040. Since 2009, Chinese government has released a series of NEVs subsidy policies to drive the substitution of fuel vehicles with NEVs. Up to now, close to 150 billion RMB worth of cumulative subsidies has been provided, and 2.62 million charging facilities and 1,298 battery-swapping stations have been erected in the country, enabling a large infrastructure network to serve nearly 8 million NEVs[7]. At the moment, China has become the largest electric vehicle (EV) market in the world where also resides the most innovation dynamic for e-mobility business model.

Lithium-ion battery industry: Battery is the key part of NEVs as it takes up about 40% of the total cost. The accelerated growth of the NEVs sector has provided momentum for the rapid development of the upstream lithium battery industry. China has become the largest lithium battery consumption market in the world for five consecutive years. In 2021, the global lithium-ion market size reached 545GWh, of which, China took up around 59.4%, reaching the capacity of about 324GWh. The aggregated sales volume of China’s lithium battery companies (including exports and sales of overseas branches) reached 382GWh, with market share of 70% in the global market[8]. At the same year, China’s total output value in the sector exceeded 600 billion RMB, enabling trillion RMB club corporations like Contemporary Amperex Technology Co., Limited (CATL) to take hold in the market[9].

Photovoltaic (PV) sector: As one of the sources of clean electricity, PV power generation is more mature and safer than nuclear energy technology. It generates less negative impact on local environment than hydroelectric power and has wider application than wind power. Therefore, PV power generation has become an important starting point for achieving “carbon neutrality” goal. China has rolled out an array of supportive policies for PV sector since 2008 and the cumulative PV (distributed and centralized) subsidy had reached close to 108 billion RMB across the country between 2012 to 2019. Under the strong support of the government, the PV sector in China grows in sophistication. Among the top ten PV module manufacturers in the world, seven come from China, with a share of around 70% of the global production. Furthermore, Chinese solar PV companies continue to set new world records of conversion efficiency for high-efficiency cells. Over years of development, China’s PV sector now boasts a whole-industry-chain approach, ranks the top in both manufacturing capacity and market share, contributing to the significant status of solar PV products in China’s export.

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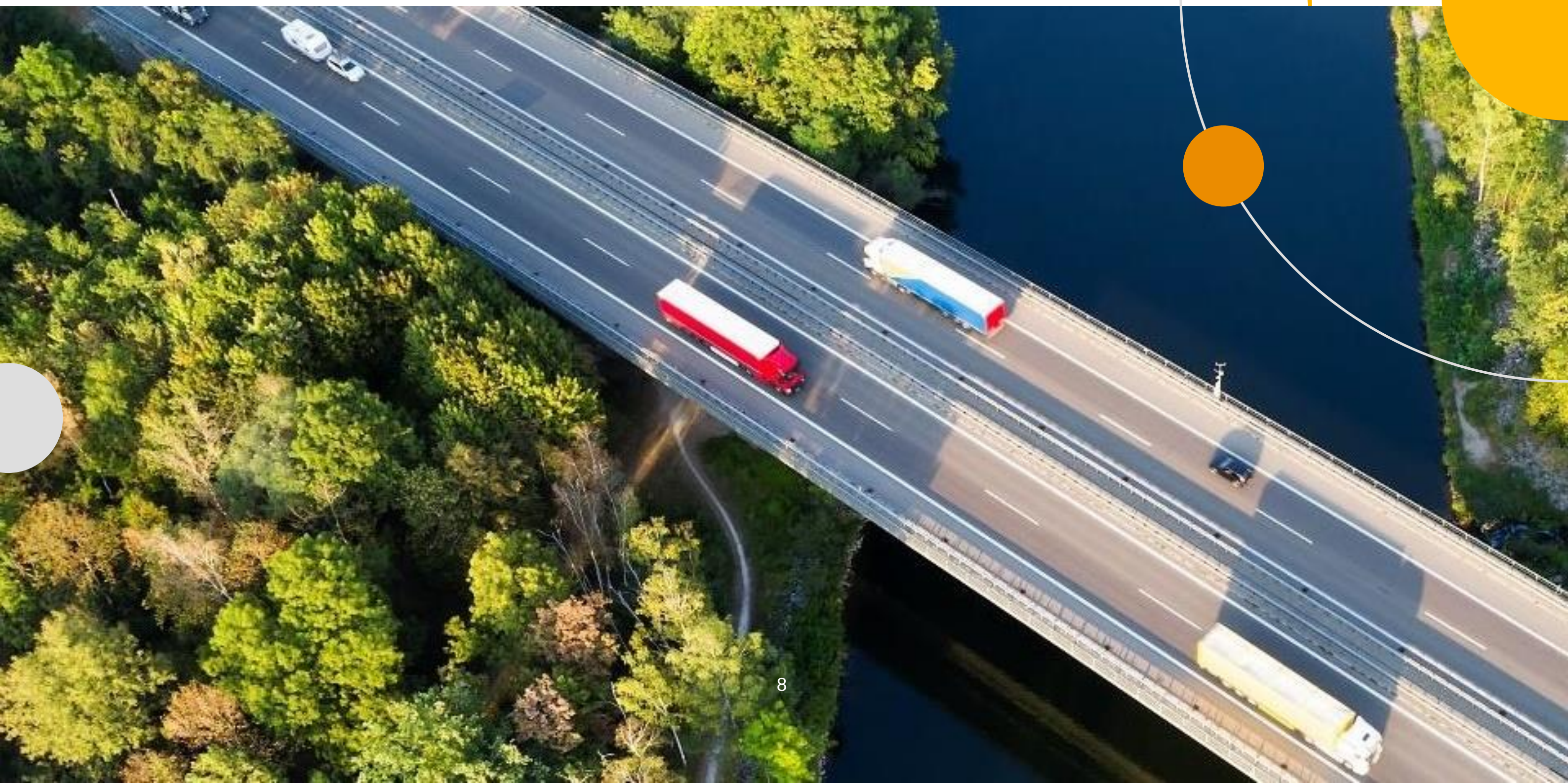
[7]《国家发展改革委等部门关于进一步提升电动汽车充电基础设施服务保障能力的实施意见》， 中国政府网

[8]《2021年锂离子电池行业运行情况》， 中华人民共和国工业和信息化部

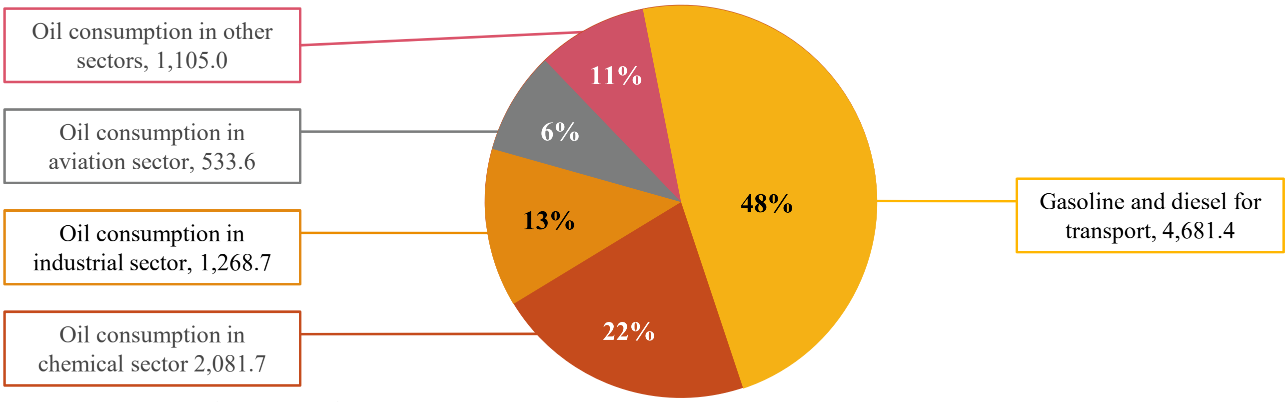
[9]《2021中国锂电产业发展指数》， 赛迪顾问



1.2.2.2 Reducing industry's oil dependence through the lens of "bio-manufacturing"

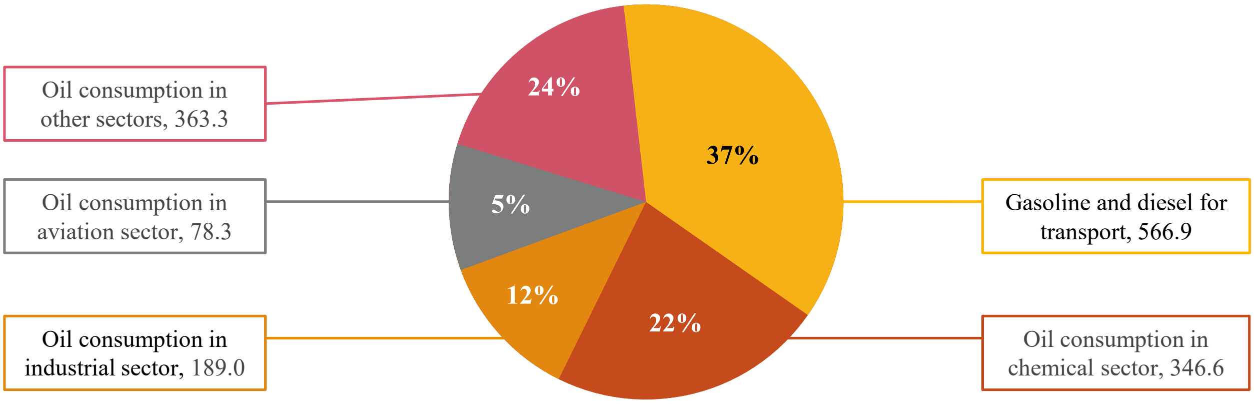
Petrochemical industry's total amount of oil consumption is the second largest, next only to traditional energy sector. The global share distribution of oil consumption by sector in 2021 showed gasoline and diesel as transport fuels consumes the largest amount of oil, reaching 48%; the second largest oil-gulping sector is petrochemical industry, taking up 22%[10]. Likewise, China's oil consumption structure shares those features. In order to curtail oil consumption in petrochemical sector and mitigate oil reserves depletion, the National Development and Reform Commission (NDRC) brings forward the idea of substituting part of petrochemical materials with bio-manufacturing ones, and consequently, reducing petrochemical sector's market size and cut oil consumption.

Share of global end-use oil consumption in 2021 (10,000 barrels/day, %)



Source: IEA, Industry Research Report

Share of China's end-use oil consumption in 2021 (10,000 barrels/day, %)



Source: BP Company, Industry Research Report

At present, the trend of partial substitution of petrochemical materials with biomanufacturing ones is on the rise. The NDRC printed and issued *"The 14th Five-Year Plan" for Bioeconomic Development*, stipulating bio-manufacturing as the strategic development path for the emerging bioeconomic sector. It is expected that the product share of petrochemicals and coal chemicals will shrink by 35% due to substitution of biomanufacturing products. Bio-manufacturing, enabled mainly by industrial biotechnology, is a new mode promised to offer green products including energy, materials and chemicals with green raw materials and process by modifying existing manufacturing process or utilizing renewable feedstocks such as biomass and carbon dioxide. As far as sources of feedstocks is concerned, bio-manufacturing can feed on multiple carbon sources including carbon dioxide, industrial exhaust, straw-converted sugar, corn, and vegetable oil. In terms of products, with the help of biotechnology, biomanufacturing can convert the abovementioned feedstocks into high value-added products in different fields, such as biodiesel, degradable plastics, bio-nylon, bio-rubber, biopharmaceuticals, bio-fertilizers, etc. Eventually, the enormous value of biology can be fully tapped to produce anything you name it, and green, low-carbon and sustainable development can be achieved in major industrial sectors such as materials, light industry, medicine, and chemical sector.

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[10]《2022-2060全球及中国原油需求展望（何时达峰？）》， 行业研究报告

1.3 Carbon neutrality strategy provides development opportunity for biodegradable material sector

1.3.1 Market Overview of biodegradable materials-the most promising material in the bio-based material market

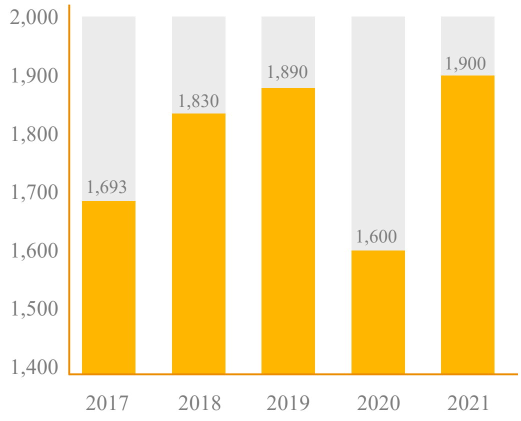
Plastic is a major downstream product of petrochemical sector and oil consumption in plastics production accounts for 8% of the global oil production[11]. According to the forecast of Natural Resources Defense Council (NRDC), worldwide plastics production will consume 20% of oil supply in the world by 2050 if the current trend remains unchecked.

According to the statistics of Plastics Europe, plastics production in 2021 grew by 6.9% compared with the level in 2018. It is expected that the capacity will double by 2035 and triple by 2050[12]. Take China as an example, the country produced roughly 62 million tons of waste plastics and recycled 31% (19 million tons) of the waste materials in 2021. On one hand, even though the remaining 69% of the plastics are disposed through landfill and incineration or discarded directly, China's still recycled 1.74 times more of its waste plastics than the global average, contributing to 70% of the total capacity for plastics recycling[13]. On the other hand, the recycling rate of United States at the same period and EU and Japan in 2020 was 5%, 35% and 24% respectively. Moreover, these countries and regions continue to ship certain plastic waste to other countries. Overall, plastic waste recycling remains to be a daunting task.

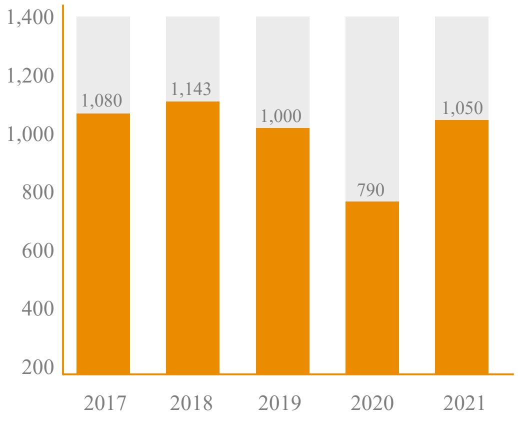
Plastic pollution has gradually morphed into the second largest environmental agenda next only to climate change. Once leaked to natural environment such as soil and water bodies, plastic barely decomposes and leads to various forms of environmental disruption including visual pollution, soil pollution and water pollution. If not handled properly, plastic also poses persistent hazards to the fragile eco-environment by contributing to greenhouse gas emissions. Furthermore, the presence of microplastics in food chain may also expose human health to severe impairment.

China is pursuing efforts to develop plastic circular economy and establish a governance system for plastic pollution by delivering progress and innovation in plastic raw materials, as well as preventing and mitigating potential plastic pollution from the source.

2017-2021
Amount of recycled plastic waste in China (unit: 10,000 tons)



2017-2021
Value of recycled plastic waste in China (unit: hundred million yuan)



Data source: Sub-association of Recycled Plastics, China National Resources Recycling Association

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[11]《中国塑料的环境足迹评估》， 北京石油化工学院、NRDC

[12] *Plastics – the Facts 2022*, Plastics Europe

[13]《中国再生塑料行业发展报告2021-2022》， 中国物资再生协会再生塑料分会

[14] *The Real Truth About the U.S. Plastics Recycling Rate*, Beyond Plastics

[15] Tokyo-based Plastic Waste Management Institute

1.3.2 Seize the opportunity: plastic restriction policies and bio-material incentives serve as morale boosters for biodegradable material development

China has rolled out a succession of restrictive policies on plastic use, boosting the development of biodegradable materials

General Office of the State Council unveiled the first “Plastic Restriction Order” in 2007, prohibiting production, sales, and use of ultra-thin plastic bags nationwide, putting into practice a charge-based system for plastic use. However, booming development in e-commerce and food delivery sectors founded on universal access to internet contributed to a soar in the demand of corresponding delivery packages and disposable cutlery, placing new burdens on China’s plastic restriction efforts. In 2017, fully biodegradable materials made into the agenda of the country’s “13th Five-Year Plan” for material sector. In 2019, National Development and Reform Commission (NDRC) released policies encouraging the development, production and application of biodegradable plastic and its series products. In 2020, NDRC and Ministry of Ecology and Environment (MEE) jointly announced *the Opinion on Further Strengthening the Control of Plastic Pollution*, proposing a three-step target achieved by 2020, 2022 and 2025 respectively, placing restrictions on the production, sales, and use of some plastic products, promoting applications of alternative products, and enhancing the effort on recycling and disposal of waste plastic. In 2021, competent authorities at provincial and municipal levels and their subordinate departments kept optimizing local plastic restriction policies to meet requirements reflected in “the 14th Five-Year Plan” on resource conservation and environmental protection. In 2022, the government released a number of policies encouraging the use and promotion of biodegradable plastic, explicitly putting forward that the country shall bolster its R&D effort on biomaterials to facilitate the development of green and low-carbon technology, as well as plastic substitution with degradable materials in application.

No.	Applications	By the end of 2020	By the end of 2022	By the end of 2025
1	Non-degradable plastic bags	Covering locales such as shopping malls, supermarkets, pharmacies, bookstores, etc., as well as takeout and food delivery services in catering sector and various exhibition activities in municipalities directly under the central government, provincial capitals and municipalities with independent planning status	Extend to cities at prefecture-level and above	Extend to fair trade markets
2	Disposable plastic cutlery	Nationwide ban on non-degradable, disposable plastic straws use in catering sector; covering restaurant dining in cities at prefecture-level and above	Extend to county-level urban built-up areas and restaurant dining at tourist attractions	Cut tableware consumption intensity by 30% in catering and food delivery sectors in cities at prefecture-level and above
3	Disposable plastic products in hospitality sector	-	Star-rated guesthouses and hotels nationwide	Extend to all guesthouses, hotels and homestay
4	Delivery plastic packages	-	Express mail service outlets in provinces and cities including Beijing, Shanghai, Jiangsu, Zhejiang, Fujian and Guangdong	Extend to nationwide express mail service outlets

According to the *Opinion*, China also will carry out enhanced governance on plastic pollution following the guideline of applying three strategies accordingly, namely, “prohibition and restriction, substitution and recycling as well as regulation”, to address different types of plastic pollution. The development of biodegradable materials, therefore, has received explicit policy support due to it being a key solution to plastic products subject to the strategy of “substitution and recycling”. Over the past few years, relevant authorities have been proactive in rolling out incentives to encourage use and popularization of biodegradable plastic. For instance, documents including *Biodegradable Straws* and *Degradation Property and Labeling Requirement for Biodegradable Plastic and Products* formulated and issued by State Administration for Market Regulation (SAMR) and Standardization Administration, and *Guiding Opinions on Promoting High-quality Development of Light Industry* jointly issued by five ministries including Ministry of Industry and Information Technology (MIIT) were put in place to explicitly advocate the development of materials relying on low-carbon technology, such as new materials and fully biodegradable plastic mulches (BDMs), and the consumption of green products such as degradable ones.

Domestic Policies

December 2007

General Office of the State Council: *Notice from the General Office of the State Council on Restricting the Production, Sales, and Use of Plastic Shopping Bags* stipulated a ban on the production, sales, and use of plastic shopping bags with a thickness of less than 0.025 mm starting from June 1st, 2008, putting in place a charge-based plastic bags use system.

December 2016

Ministry of Industry and Information Technology (MIIT), National Reform and Development Commission (NDRC), Ministry of Science and Technology (MOST) and Ministry of Finance: *Guideline on New Material Industry Development* was issued to speed up transformation and upgrade of advanced basic material industry, to vigorously drive intelligence and green based modification in the process of material production and develop biodegradable materials.

April 2017

Ministry of Science and Technology (MOST): Fully-biodegradable material was incorporated in the *Special Program Plan for Scientific and Technological Innovation in Material Sector under the "13th Five-Year Plan"*

September 2019

Central Comprehensively Deepening Reforms Commission: *Opinions on Further Strengthening of Plastic Pollution Control* was issued to place prohibition and restriction on the production, sales, and use of some plastic products in an orderly manner, to actively promote alternatives that can be recycled, products that are recycling-friendly and biodegradable, to strengthen the supply of green products, to regulate recycling of plastic waste, to establish and improve management systems at all levels and to take strong, planned and effective measures to address plastic pollution issues.

October 2019

National Reform and Development Commission (NDRC): *Industrial Structure Adjustment Guidance Catalogue (2019 Version)* was released to encourage the development, production and application of biodegradable plastic and its series products.

January 2020

National Reform and Development Commission (NDRC) and Ministry of Ecology and Environment (MEE): *Opinions on Further Strengthening of Plastic Pollution Control* was issued to limit the production, sales, and use of some plastic products with a three-step target, of which milestones are set to be achieved by 2020, 2022 and 2025 respectively.

June 2021

National Government Offices Administration and National Reform and Development Commission (NDRC): *Notice on Printing and Issuance of the "14th Five-Year Plan" for Energy and Resources Conservation in Public Institutions* was announced to phase out the use of non-degradable, disposable plastic products in the public institutions.

July 2021

National Reform and Development Commission (NDRC): The *"14th Five-Year Plan" for Circular Economy Development* was issued to cut the use of plastic products from the roots, place rigorous restrictions on the production of ultra-thin plastic mulches and discourage the use of disposable plastic products by citizens.

2022

State Administration for Market Regulation (SAMR), Standardization Administration and Ministry of Industry and Information Technology (MIIT): *Biodegradable Straws, Degradation Property and Labeling Requirement for Biodegradable Plastic and Products, and Guiding Opinions on Promoting High-quality Development of Light Industry* were issued to consolidate R&D efforts on biomaterials and specifically advocate a green and low-carbon oriented development path towards biomass alternative application.

EU and US lead the pace to roll out "Plastic Limit Orders" to restrict plastic products use around the world

In December 2015, the European Union launched the *Circular Economy Action Plan (CEAP)*, advocating to create a framework for sustainable products. The action plan defined plastic as one of the seven key product sectors, explicitly proposed to increase value and reduce amount of waste and move away from overdependence on overseas waste disposable capacity. In January 2018, the European Union adopted the *EU Plastics Strategy*, which aims to transform the way plastic products are designed, produced, used and recycled in the EU. In May 2018, the European Union put forward rules on *Single-Use-Plastics (SUP),* aiming to reduce plastic waste. In February 2019, aiming to build a global plastics pact network, *European Plastics Pact* was released under the joint effort of Netherlands and France and over eighty other organisations (governments, companies, non-governmental organisations and business associations) from across Europe. In August 2020, US launched *U.S. Plastics Pact*. By 2021, there had been 10 national and 2 regional pacts joining the global plastics pact network.

International Polices

December 1st, 2015

European Union launched the *Circular Economy Action Plan (CEAP)*, advocating to create a framework for sustainable products. The action plan defined plastic as one of the seven key product sectors, explicitly proposed to increase value and reduce amount of waste and move away from overdependence on overseas waste disposable.

January 1st, 2018

European Union adopted *Plastics Strategy in Circular Economy*, which aims to transform the way plastic products are designed, produced, used and recycled in the EU.

May 1st, 2018

European Union put forward rules on *Single-Use-Plastics (SUP)*, aiming to reduce plastic waste.

February 1st, 2019

Aiming to build a global plastics pact network, the *European Plastics Pact* was released under the joint effort of Netherlands and France and over eighty other organisations (governments, companies, non-governmental organisations and business associations) from across Europe.

August 1st, 2020

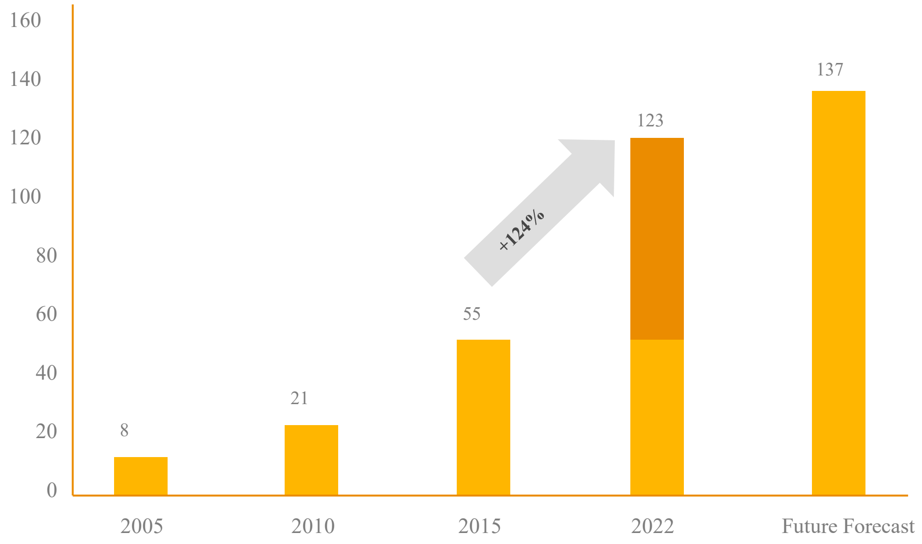
US launched *U.S. Plastics Pact* and embraced circular economy for plastics

2021

There had been 10 national and 2 regional pacts joining the global plastics pact network.

Besides European countries and US, stakeholders in other countries and regions have also taken initiative to restrict the use of single-use-plastics. In 2015, there had been 55 countries and regions adopting restrictive measures against the use of disposable plastics. By 2022, the number has jumped to 123, an increase of 124%[16]. In March 2022, representatives from 175 countries and regions adopted the *Resolution to End Plastic Pollution (Draft)* at the Fifth United Nations Environment Assembly (UNEA-5), with the ambition of completing the world's first "Plastic Restriction Order" by the end of 2024.

Cumulative number of countries and regions placing restrictions on single-use plastics between 2005 and 2022



Source: The Nicholas Institute for Energy, Environment & Sustainability

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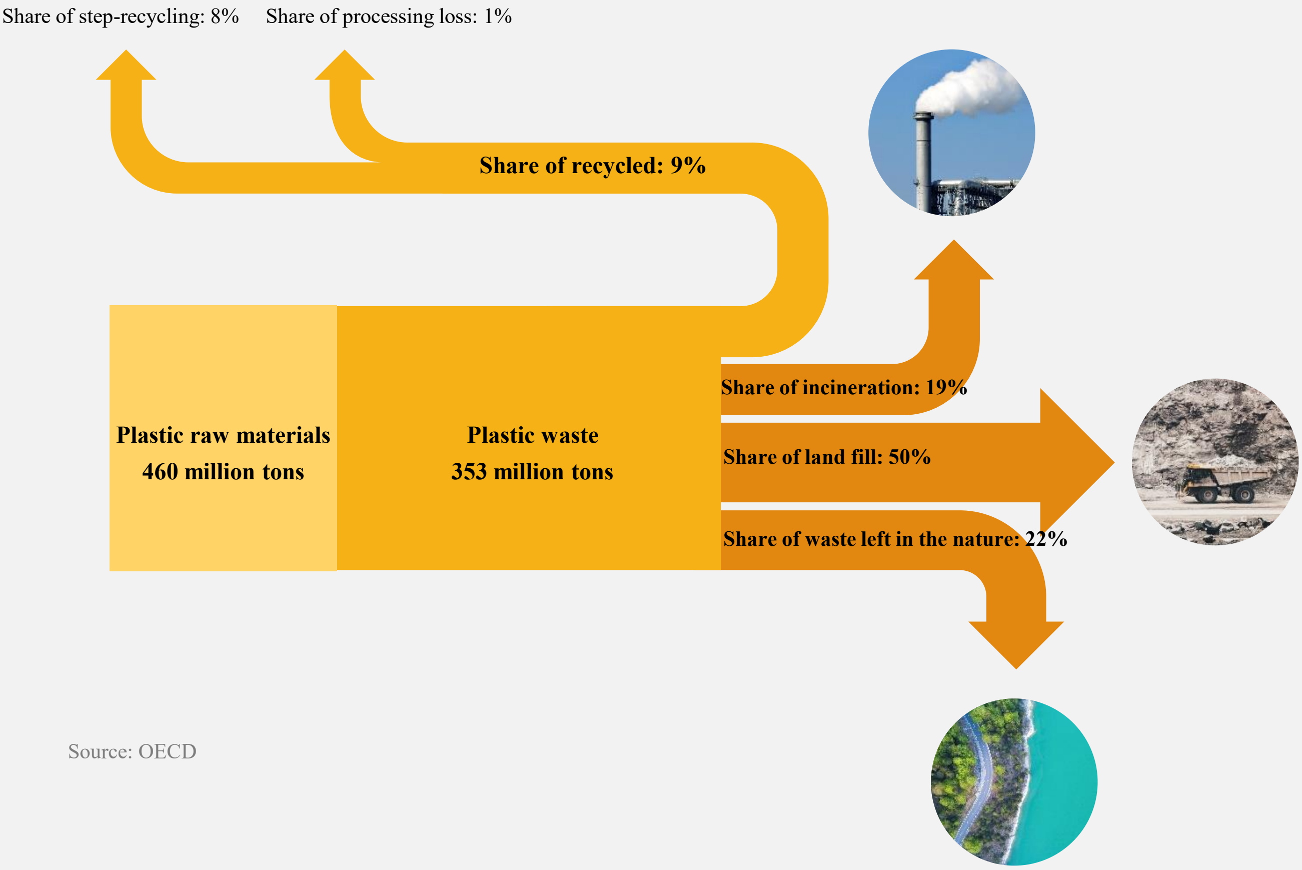
[16] The Nicholas Institute for Energy, Environment & Sustainability

There is an evident demand for the substitution of petroleum-based plastic packaging in the world and the market prospect is promising

Against the global megatrend of plastic restrictions, packaging application presents as the segment with the most pressing need for alternatives to petroleum-based plastic[17].

- In terms of volume, packaging takes up 40% of the plastic produced.
- In terms of recycling, the *Global Plastics Outlook* prepared by OECD identifies that the volume of global plastic waste reached 353 million tons in 2019, of which only 9% were recycled, 19% were incinerated and close to 50% were sent to sanitary landfill sites. The remaining 22% were either dumped in wasteyards, burned in the open or leaked to the environment[18].
- In terms of economic losses, according to the statistics from MacArthur Foundation, over 95% of the value of plastic is lost after being used briefly and an annual loss of 80 to 120 billion dollars can be attributed to packaging use. Moreover, the cost of negative externalities after plastic use combined with the loss due to greenhouse gas emission in plastic production process is up to 40 billion dollars, going beyond the gross profit of plastic packaging segment.

Circulation of plastic package material in 2019



Source: OECD

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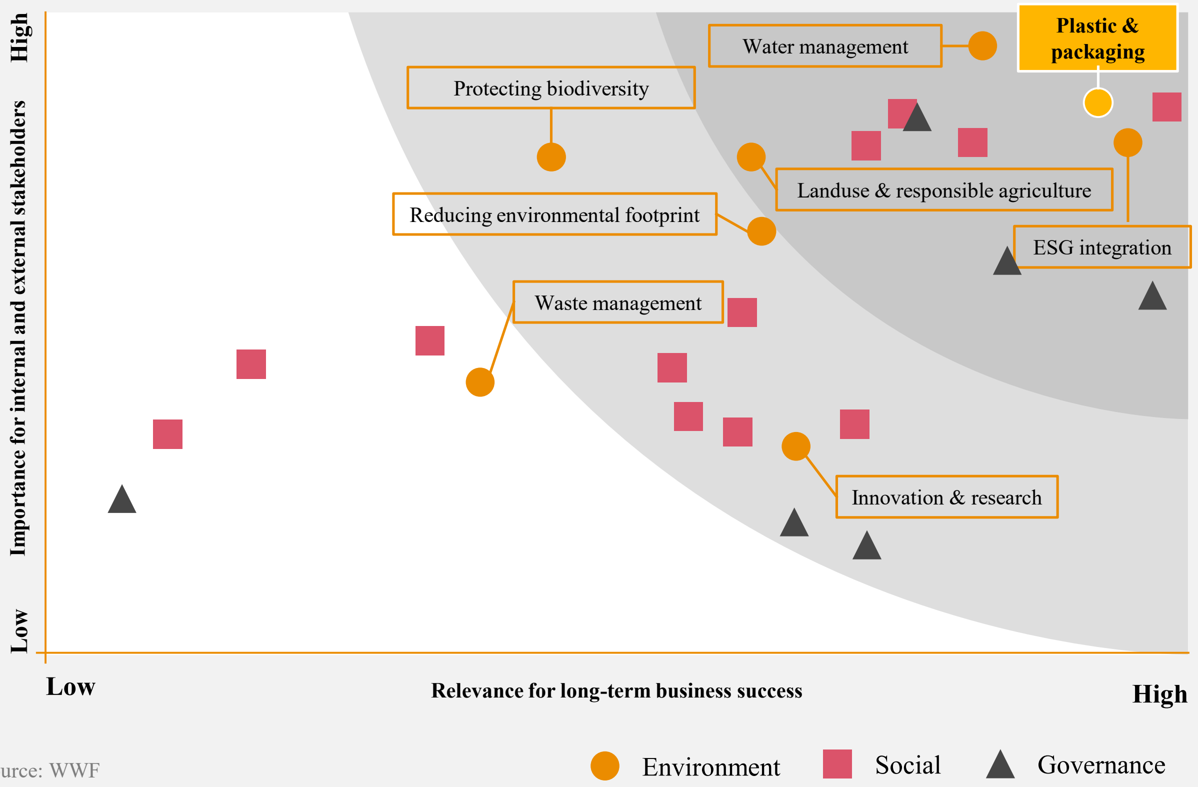
[17]《中国塑料包装再生现状白皮书》， WWF

[18] Global Plastics Outlook: *Economic Drivers, Environmental Impacts and Policy Options*, OECD

Plastic pollution and recyclable packaging are identified across major fast moving consumer goods companies (FMCG) as one of the most significant ESG issues to address, important for both internal and external stakeholders, and relevant for long-term business success[19]. In recent years, top corporate users of plastic packaging have started rethinking their value proposition and evolving their business models to secure competitive advantage in line with the principles of a circular economy. Led by the Ellen MacArthur Foundation, in collaboration with the UN Environment Programme, the *Global Commitment* has united more than 500 companies and organizations, representing 20% of all plastic packaging produced globally, behind the common vision of a circular economy for plastics-a commitment to realising the 2025 targets of addressing the root issues of plastic pollution and making sure all packaging materials are designed to be reusable, recyclable or compostable. Major plastic packaging companies, packaging suppliers and raw material suppliers sharing this vision serve as predominant sources of clients for biodegradable plastic producers.

Part of the companies behind the *Global Commitment*

Plastic is the number one ESG issue major FMCG companies are attempting to address



Source: WWF

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[19] The Business Case for a UN Treaty on Plastic Pollution, WWF

1.3.3 Application advantages: biodegradable materials are the best alternatives to conventional plastics

At present, alternatives to traditional plastics include conventional non-petrochemical-derived materials (such as glass, ceramics, metals and papers) and biodegradable materials. The latter can be divided into petroleum-based and bio-based ones, with bio-based degradable materials being more superior:

- **Biodegradable materials are more versatile in terms of application when compared with traditional non-petrochemical-derived ones**

Traditional alternatives are hindered by numerous limitations: Glass and ceramics are relatively thick, heavy and delicate, adding difficulties to shipment; Metals are relatively more energy-intensive in the process of manufacturing and are prone to corrosion. Besides, metals are limited in terms of application scope; Papers are relatively poor in durability and are prone to be damaged by water. Moreover, paper making is a process that generates more waste and consumes a large volume of water resources; Wood products are costly and poses a concern for excessive deforestation. In comparison, biodegradable materials face less restrictions as alternatives to plastics due to their plastic-like properties.

- **Different from oil-based degradable materials, bio-based ones are more competitive in upstream feedstock supply and production process**

Feedstock of bio-based degradable materials are more sustainable: The upstream feedstock of oil-based degradable materials are non-renewable petrochemical resources. Take PBAT as an example, the petroleum-based degradable materials are derived mainly from Purified Terephthalic Acid (PTA), Butanediol (BDO) and Adipic Acid (AA), all of which are petrochemicals. Biodegradable Materials Research Institute identifies that 1 ton of PBAT production consumes 0.4 ton of PTA, 0.43 ton of BDO and 0.35 tons of AA[27]. Among them, the production of BDO is energy intensive as 95% of BDO production facilities in China adopt Reppe method, a method that consumes a large amount of electricity. On the contrary, bio-based degradable materials use renewable biomass as their feedstock (such as sugars and vegetable oils), and long-term upstream feedstock supply can be secured since a large amount of non-food biomass is produced globally each year.

Production of bio-based degradable materials induces less safety concern: There lies multiple safety risks behind the production process of petrochemical materials as many chemical catalytic reactions require high-temperature and high-pressure conditions, resulting in high level of accident risks. Take PBAT as an example, the three esterification processes for its production require a temperature higher than 140°C, and more so is the polycondensation reaction following esterification, demanding a temperature range of between 240°C-255°C. On the contrary, bio-fermentation usually takes place under room temperature and atmospheric pressure, enabling a relatively low risk level for accidents.

Bio-based degradable materials share the merits of traditional plastics due to their resemblance to plastics in physical and mechanical properties. At the same time, being degradable and bio-based derived, the materials offer solutions to two of the most criticized problems caused by traditional plastics, namely, plastic pollution due to degradation-resistance and aggravation of greenhouse gas emission. Bio-based degradable materials are more versatile application when compared with other plastic alternatives; the upstream feedstock supply of bio-based plastics is more sustainable and production process safer when compared with that of the petroleum-based degradable materials. In conclusion, bio-based degradable materials are undoubtedly the most critical alternatives to conventional plastics.

2

PHAs:
The most promising biodegradable materials

PHAs are superior in both degradability and application versatility when compared with other degradable materials: In terms of degradability, PHA is biodegradable in various environments covering freshwater, marine environment, soil, compost and even organic sludge. PHAs and other materials can also be compounded to enhance degradability of final products; In terms of physical property, since PHAs are a series of polymers, different monomers can be combined to form a variety of copolymers, and the polymers can compound with other degradable materials to improve physical and mechanical properties of polymer composites.

Meanwhile, PHAs promise enormous market potential and boast adequate supply capacity. Market size of the polymer family is expected to reach 1.2 trillion RMB, completely replacing PP and PE in the packaging segment as its production cost continues to decrease.

2.1 Degradability: PHAs possess superior degradability as a class of degradable plastics

Four major biodegradable polymers can be distinguished: ① Polymers produced from biomass, such as starch, cellulose, lipids and proteins; ② Polymers produced by microorganisms, such as PHA family; ③ Polymers obtained through chemical synthesis of bio-derived monomers, such as PGA and PLA; ④ Polymers obtained through chemical synthesis of petroleum-derived monomers, such as PBSA and PBAT.

• Degradation mechanisms of PHA and other degradable materials

PHA biodegradation process includes the following steps: First, PHA depolymerase secreted by microorganisms will turn hydrophobic PHAs into hydrophilic form through hydrolysis, the soluble PHAs are then absorbed and utilized by microorganisms again to produce carbon dioxide and water. Therefore, PHA degradation takes place in environments with relatively high microbial activity, such as soil, lake, marine environment and even sewage and sludge.

PLA is a polymer produced through chemical synthesis of biological-derived lactic acid monomers. Essentially, it is not a natural polymer. Before PLA degradation takes place, low molecular weight polymers are produced by hydrolyzing the ester-bond backbone of the polymer through water absorption. Then the low molecular weight polymers are decomposed into carbon dioxide and water by microorganisms. PLA degradation conditions are rather demanding as polymer hydrolysis requires high-temperature and high-humidity in the compost, making it difficult for the reaction to take place in natural environment.

PBAT stands for polybutylene adipate terephthalate. In the process of degradation, the polyester will first undergo hydrolysis to become mono-methyl terephthalate and terephthalic acid, and then further decompose into carbon dioxide and water. Since PBAT are mainly decomposed by thermophilic actinomycetes, a class of microorganisms usually found in soils and not so much in water bodies, therefore, it is difficult for PBAT to degrade in freshwater and marine environments[20].

• PHA is degradable in various environments

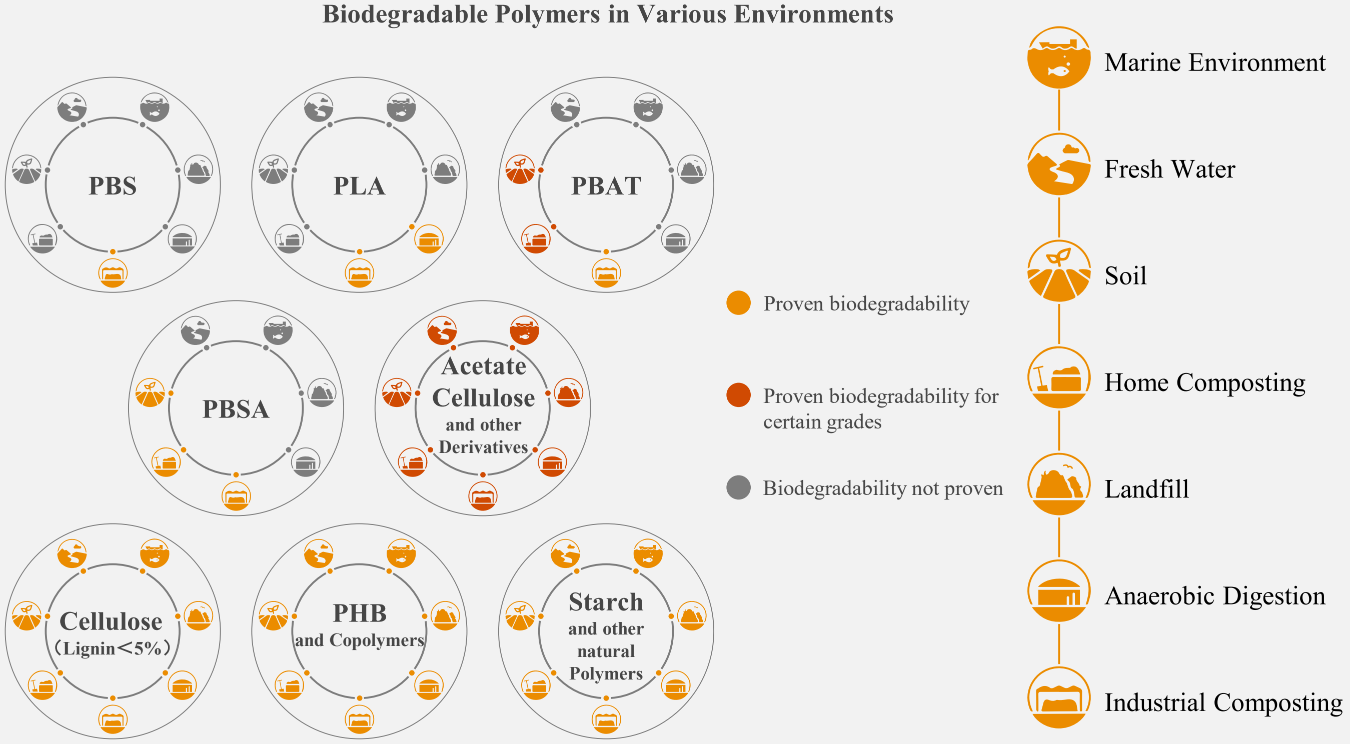
According to established standards & certification schemes, Nova Institute outlined an illustration of Biodegradable Polymers in Various Environments:

① PLA is only biodegradable in industrial composting and anaerobic digestion environments;

② PBAT is only degradable in certain soils, home composting and industrial composting environments;

③ PHA (includes PHB and its polymers) is degradable in various environments, including soil, fresh water, marine environment, home composting, industrial composting and anaerobic digestion.

Biodegradable Polymers in Various Environments



Source: Nova Institute

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[20] *Occurrence and Analysis of Thermophilic Poly(butylene adipate-co-terephthalate)-Degrading Microorganisms in Temperate Zone Soils*, Jana, et.al., Int J Mol Sci

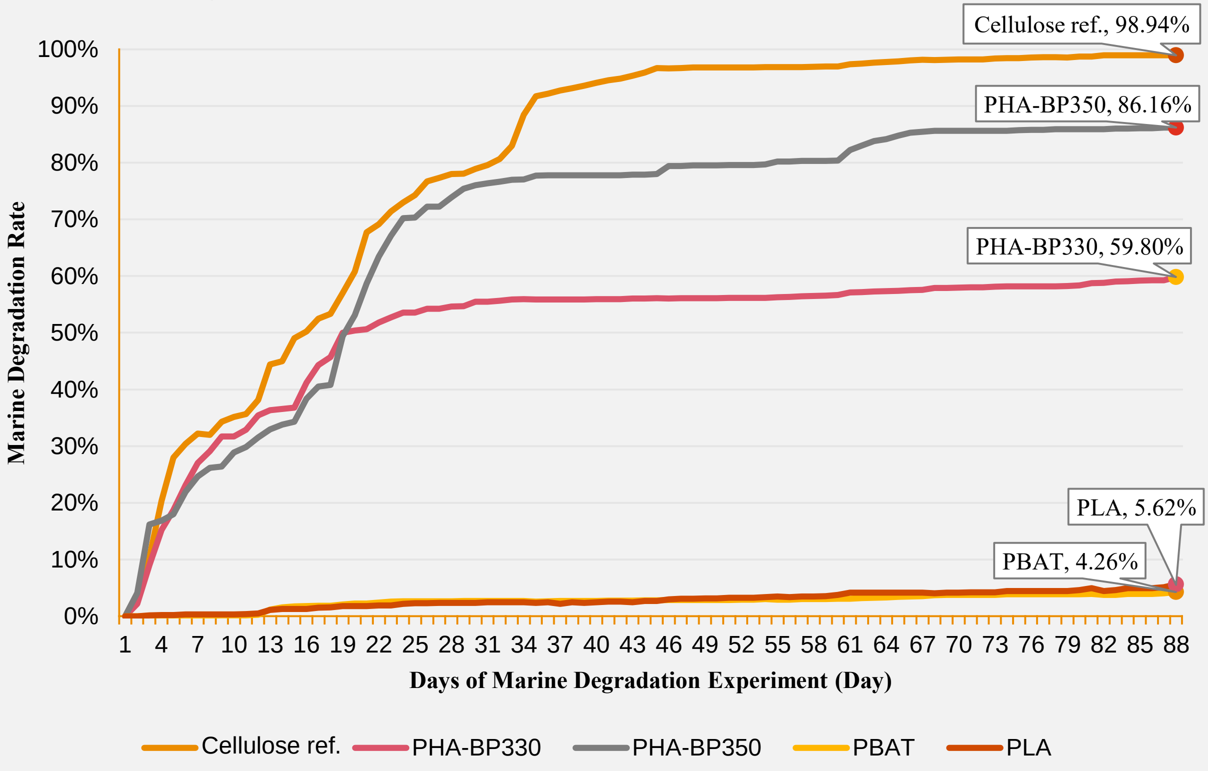
• PHA and other materials can be mixed to offer better degradability

Due to desirable degradability of PHA in various natural and artificial environments, producers of various other degradable materials are actively experimenting on blending materials with PHA to improve product degradability. For this end, Bluepha partnered with PJCHEM to experiment degradability of PHA blended with PBAT and PLA respectively in marine environment. The two sides obtained the following outcomes after 87 days of experiment:

① Degradability of PHA virgin materials exceeds 86% in marine environment, while degradability of PBAT and PLA virgin materials is only 4.3% and 5.6% respectively;

② When mixing PLA with PHA, maximum degradability of the blend polymer is over 75%;

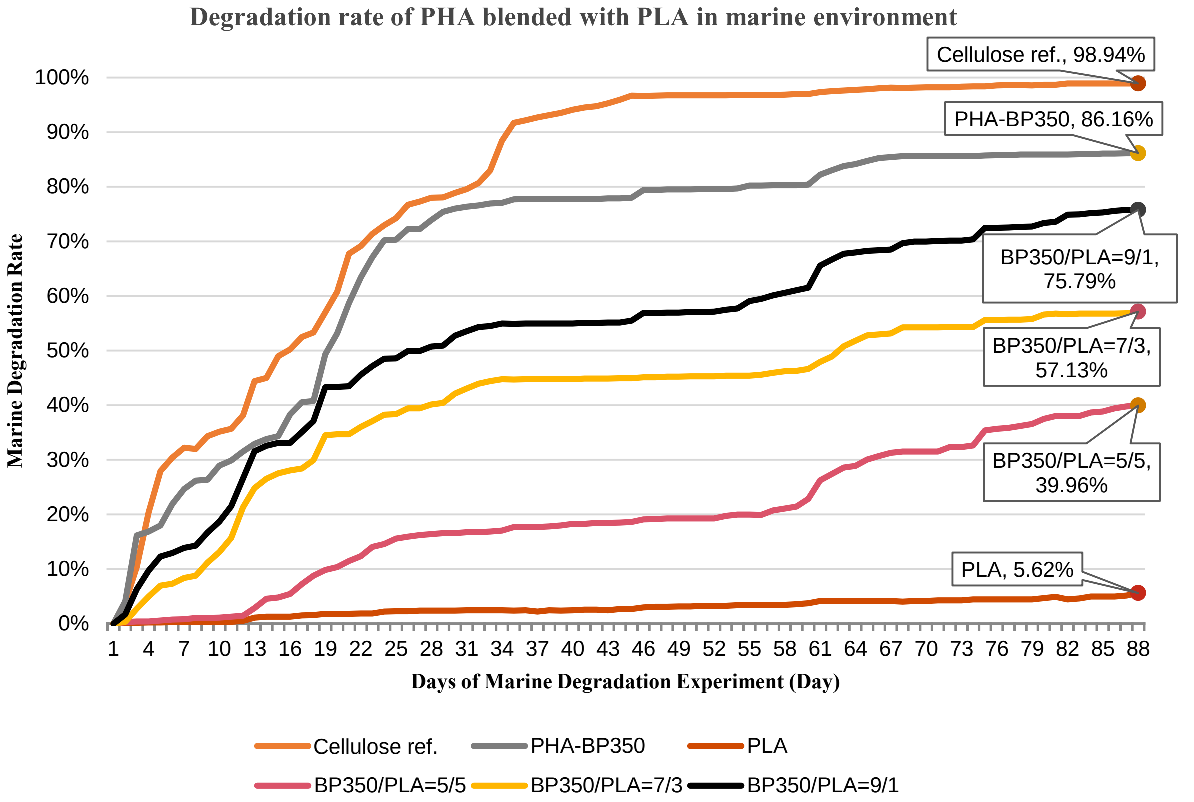
③ When mixing PBAT with PHA, degradability of the blend polymer exceed 65%.



Degradation rate of PHA blended with PBAT and PLA in marine environment

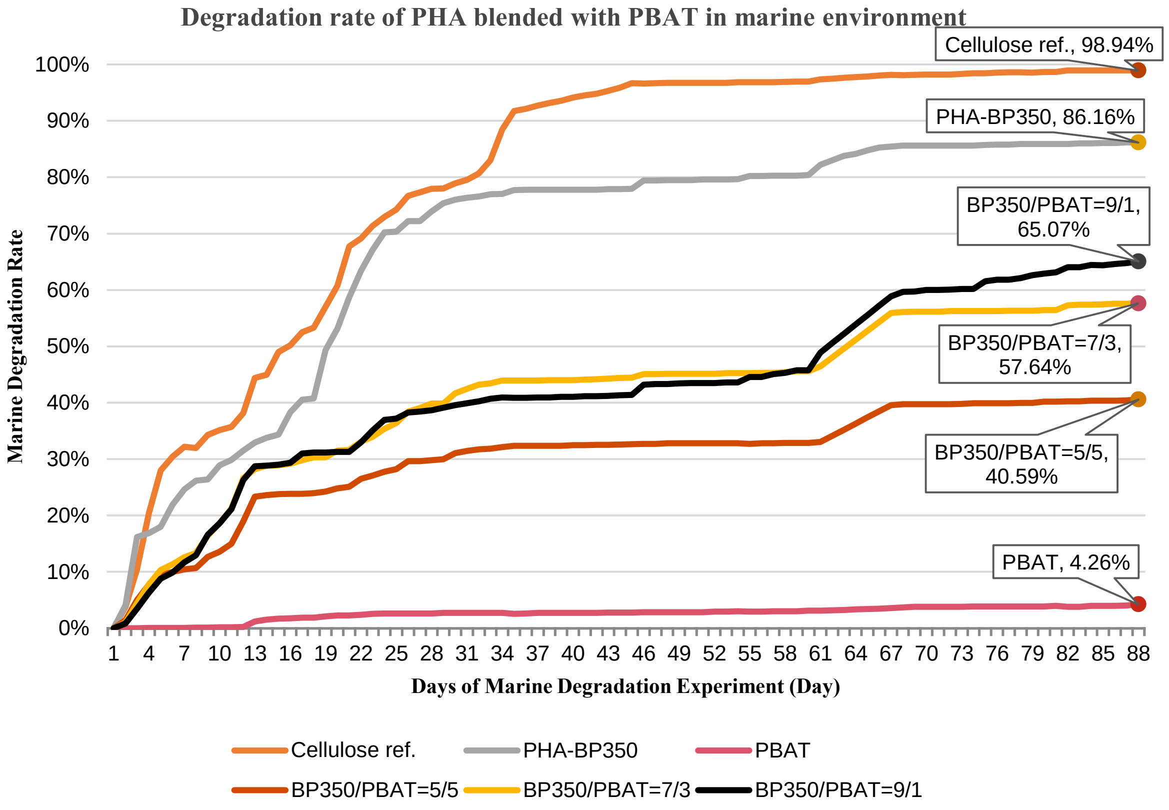
Note: polymer grades used in the experiments are Bluepha PHA BP350, Total Corbion PLA LUMINY® L175, Blue Ridge Tunhe PBAT TH801T

Source: Bluepha, PJCHEM



Note: polymer grades used in the experiments are Bluepha PHA BP350, Total Corbion PLA LUMINY® L175, Blue Ridge Tunhe PBAT TH801T

Source: Bluepha, PJCHEM



Besides natural macromolecules such as cellulose containing less than 5% of lignin and starch, PHA is the only polymer that is biodegradable in various environments. Plastics leakage to natural environments like soil and water bodies tends to happen in our daily lives, therefore, PHA offers an excellent solution to the problem with its degradability in various natural environments.

- **With national infrastructure foundation for composting being weak, the adoption of PHA is poised to relief the burden on plastic disposal**

To be biodegradable, other degradable materials such as PLA require industrial composting and anaerobic digestion treatment to become low molecular weight polymers first through hydrolysis. However, infrastructure foundation for composting and anaerobic digestion is weak in China. Take domestic waste disposable as an example, currently, landfill remains the predominant way of waste treatment and capacity for composting and anaerobic digestion is relatively limited. According to the *Annual Statistic Report on Environment in China*, the total amount of domestic waste was 270 million tons in 2020, among them 220 million tons were sent to landfill sites, only 890,000 tons were composted, 3.569 million tons were treated through anaerobic digestion, and 949,000 tons were biodegraded. For food waste, the first option to consider is composting and anaerobic digestion, yet food waste takes up 37% to 62% of the entire municipal waste in China, overburdening the capacity of existing facilities for composting and anaerobic treatment[21].

The journey to build more facilities for composting and anaerobic digestion is long and arduous. For starters, the cost of the two options is higher than that of the others. Therefore, more capital investment needs to be in place before lifting the proportion of waste treated with these two options. Secondly, composting and anaerobic digestion require extensive, rigorous implementation of waste sorting system. If harmful chemical substances such as heavy metals are found in compostable waste, it will only aggravate the impact on environment. Thirdly, there is still no complete standards and management system for composting in China and the absence of such standards makes it challenging to scale up treatment facilities.

Being a polymer without the need for special treatment of composting and anaerobic digestion against such a backdrop, PHA offers a readily degradable solution that will undoubtedly be a substantial relief from the burden on plastic disposal efforts.

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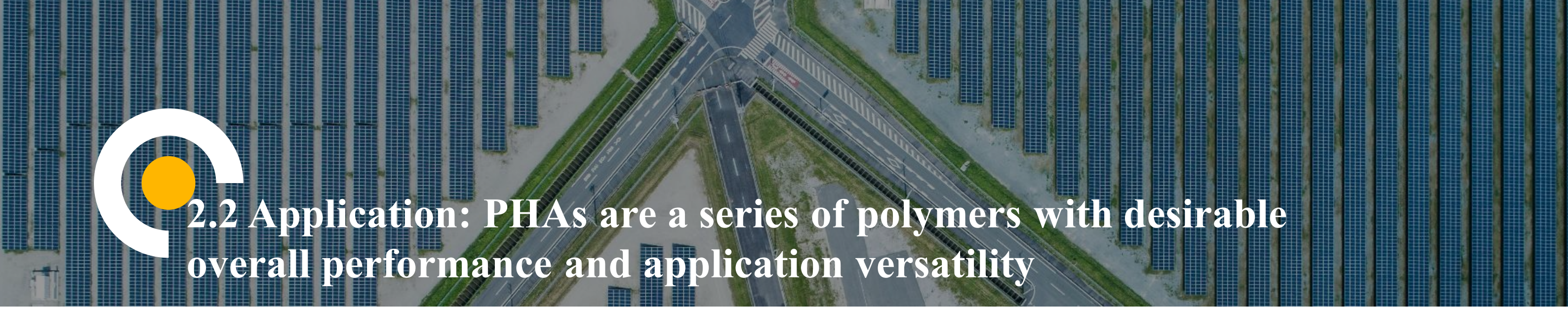
[21]《2020年中国生态环境统计年报》， 生态环境部

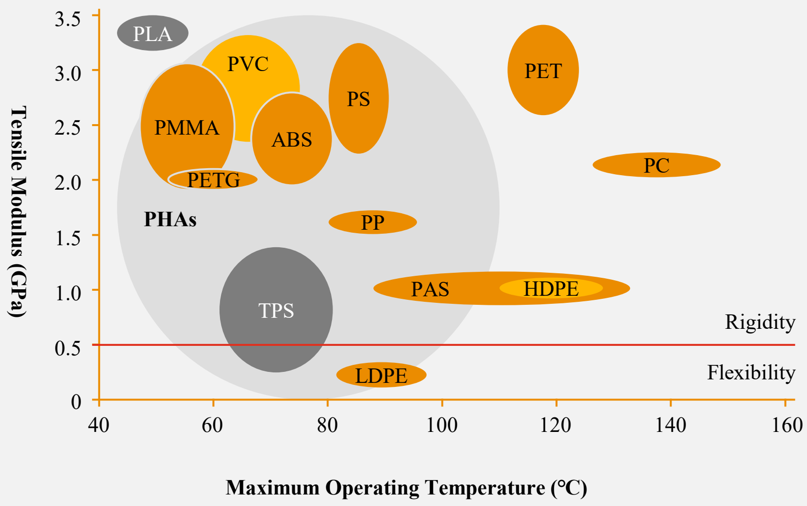


2.2 Application: PHAs are a series of polymers with desirable overall performance and application versatility

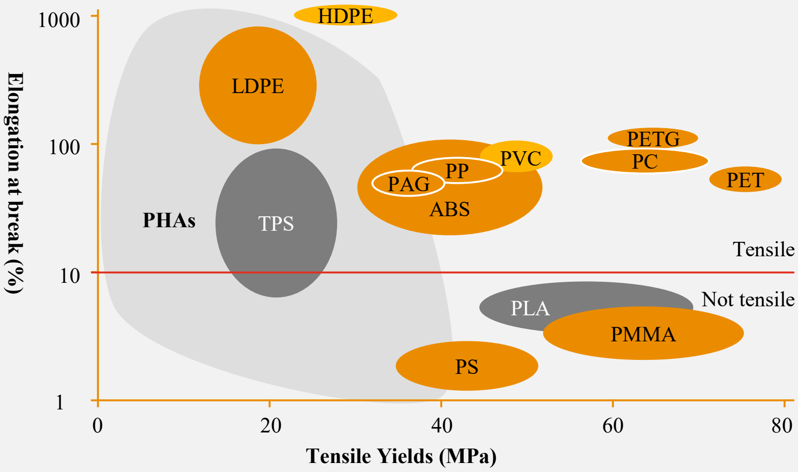
• PHA family spans a wide indicator interval of physical properties

PHA is a class of natural polyesters produced by microorganisms. At the moment, over 150 different structural units or monomers have been discovered for the polymer family. Among these product families are PHB, PHBV and PHBHHx (also known as PHBH and hereafter referred as PHBH) and others, each of them span a different range of properties. According to GO!PHA, the largest industry organization for PHA in the world, PHA product family spans a wide indicator range of physical properties[22]:

- Molecular weights ranging between 300,000 and 1,000,000 kDa;
- Polymer melt temperatures for crystalline products ranging between 60 and 170° C;
- Tensile modulus ranging between 10 and 1,000 MPa;
- Tensile yields ranging between 1 and 45 MPa;
- Elongations ranging between 1% and 1,000%.



Compared with other petroleum-based and bio-based thermoplastic materials, PHA product family's design space for thermal mechanical property is wider (polymers span a wide interval of application temperature and tensile modulus)



Compared with other petroleum-based and bio-based thermoplastic materials, PHA product family's design space for mechanical property is wider (polymers span a wide interval of tensile strength and elongation at break)

Source: Cambridge Consultants

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[22] Polyhydroxyalkanoates (PHA) An emerging and versatile polymer platform, Jan Ravenstijn, GO!PHA

The wide range of properties is a clear demonstration that one cannot simply talk about PHA as a single product.

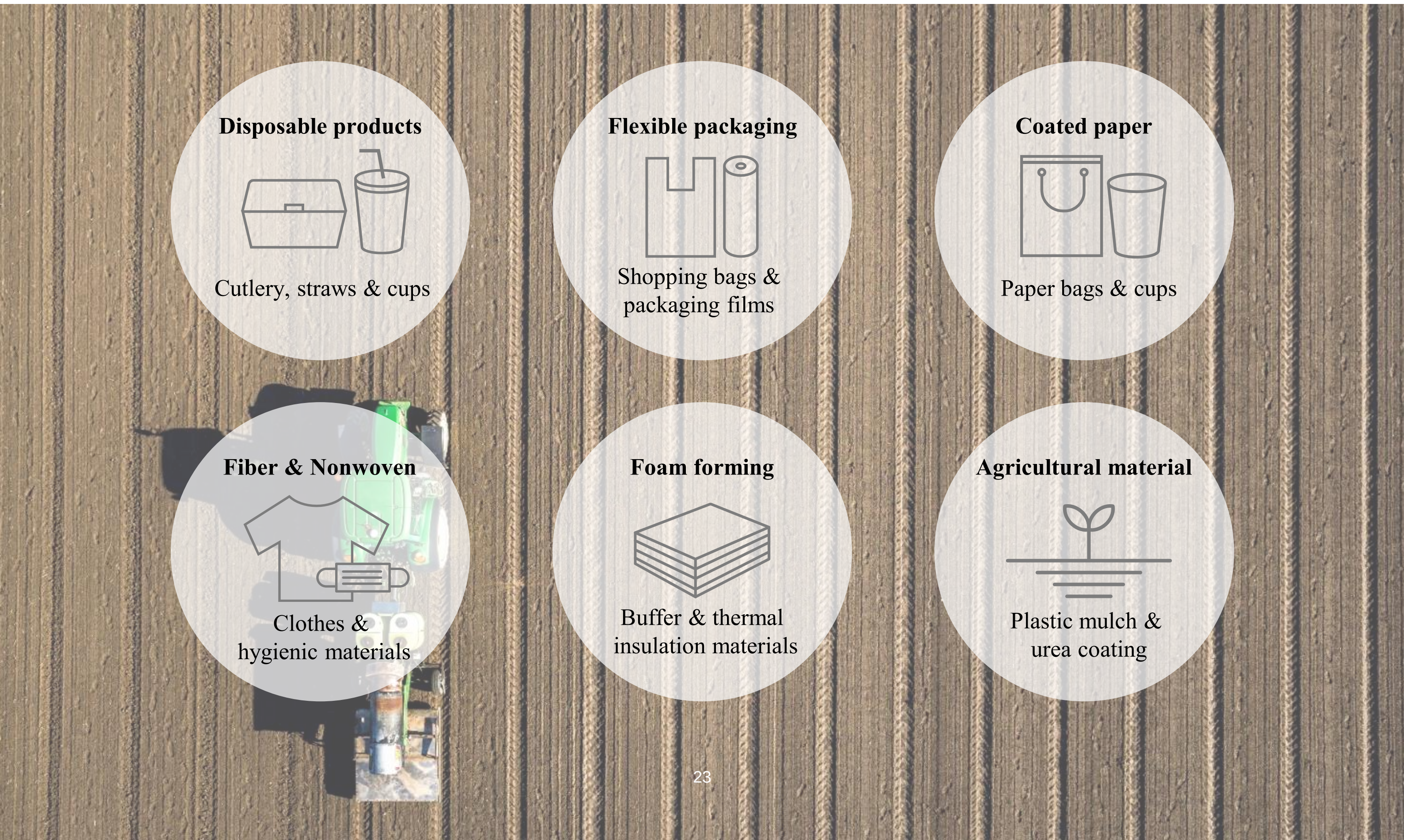
- **Sound overall performance of PHA**

Compared with degradable materials such as modified starch, PBAT and BLA, PHA offers better comprehensive property.

Project		Starch-based	PBAT	PLA	PHA
Resource Utilization		Bio-based	Petroleum-based	Bio-based	Bio-based
Ways of Production		Chemical modification	Chemical synthesis	Chemical synthesis	Bio-synthesis
Main properties of materials	Strength	Medium	Relatively high	High	Relatively high
	Toughness	Poor	Good	Poor	Relatively good
	Barrier property	Poor	Poor	Medium	Good
	Others	Not resistance to hydrolysis	Flexible and uniform	Good transparency, relatively high brittleness	Biocompatible and modifiable
Processibility		Poor	Relatively good	Relatively good	Relatively good
Storage performance		Poor	Medium	Poor	Relatively good
Degradability	Composting	√	√	√	√
	Soil	√	√	×	√
	Water bodies	×	×	×	√

- **PHA product families offers application versatility**

PHA product families span a different range of properties, therefore, the polymers possess great versatility in application. For instance, single-use products, flexible packaging and plastic-coated paper. In addition, products with better physical and mechanical properties can be obtained by adjusting PHA product composition either through blending different PHA structural units (corresponding to different physical and mechanical properties) or combining PHAs with other degradable materials. For example, PHA blended with PLA offers improved product toughness, and PHA blended with PBAT provides products with better strength profile.



2.3 PHA boasts enormous market potential

This section provides a forecast on PHA market size at different stages, the estimation is shown in the following chart. It is clear that the PHA market size can reach around 62.9 billion yuan, 355.3 billion yuan and 1.2 trillion yuan respectively in short-term, medium term and long-term.

PHA sector stages	Market size	Related note on estimation
Short-term PHA market (2025)	62.86 billion yuan	The data is based on estimation rationale for the medium-to-short term PHA market and partial hypothetic calculation of the short-term market, part of the data source is the same as the data from the medium-term market
	44 billion yuan	The data is based on the statistics of demand estimation for compostable materials by MacArthur Foundation
Medium-term PHA market (2030)	355.33 billion yuan	The data is based on estimation rationale for the medium-to-short term PHA market and partial hypothetic calculation of the medium-term market, part of the data is sourced from Statista, Grandviewresearch, Plasway, ScienceNet.cn, Sumibuy.com, IPO prospectus of Zhejiang Hisun Biomaterials Co., Ltd., and industry research reports
Long-term final PHA market (2040)	1,250.74 billion yuan	The data is based on estimation rationale I for the long-term PHA final market, part of the data is sourced from Statista, National Graphic, Plastics the Fact 2019
	1,242.2 billion yuan	The data is based on estimation rationale II for the long-term PHA final market, part of the data is sourced from Grandviewresearch, Statista, Research and Markets, Plasway

2.3.1 Short-term market (2025)

- **In the short-term, the product cost of PHA will still be higher than that of the PLA, and the predominant market need lies in scenarios where materials recycling is not convenient and environmental leakage tends to happen. The market size will be about 62.9 billion yuan.**
- **By 2025, a demand of 1.25 million tons of PHA can be reached just from member companies of MacArthur Foundation, and correspondingly, the entire market size of PHA will reach 44 billion yuan.**

2.3.1.1 Short-term PHA market size: 62.9 billion yuan

In the coming three to five years, the predominant short-term PHA market are segments such as plastic bags, plastic mulch and disposable cutlery, where recycling effort is painstaking but much needed. During this period, market penetration of PHAs in degradable plastics category will remain to be relatively low.

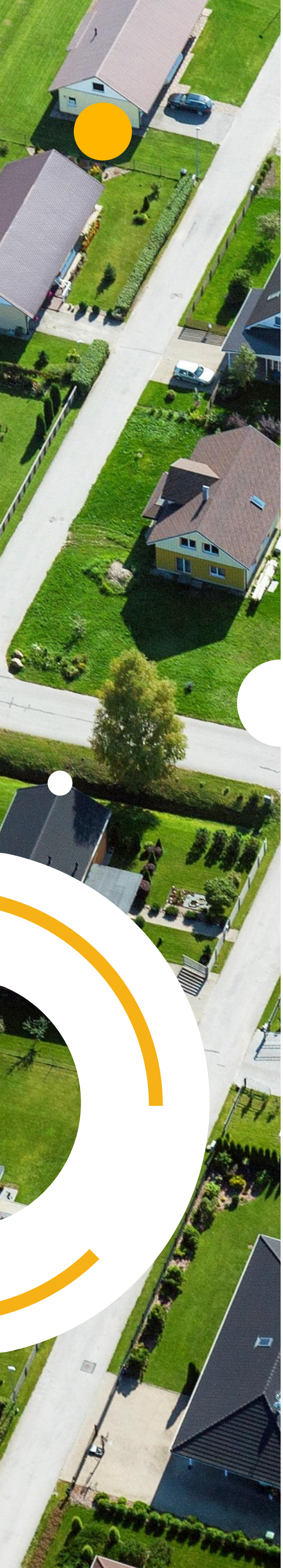
In this section, estimation rationale for medium-term PHA market will continued to be adopted for the calculation of the short-term market size, and various data hypotheses adjusted according to the short-term market are shown in the following:

① Within the next three to five years, PHA production will cost around 30% more than PLA production, and price will be around 1.5 times to that of the PLA;

② Compared with medium-term market, degradable plastics penetration in segments including plastic bags, plastic mulch, disposable cutlery and other plastic packaging film materials in the short-term market is relatively lower, assuming to be 30%, 20%, 30% and 10% respectively;

③ Compared with the medium-term market, market penetration of PHA polymers, as a category of degradable plastics, in segments including plastic bags, plastic mulch, disposable cutlery and other plastic packaging film materials in the short-term market is relatively lower, assuming to be 2%, 5%, 15% and 1% respectively.

In the short-term market, unit selling price of PHA is 35,000 yuan/ton. It is predicted that within the next three to five years, market demand of PHA will be around 1.8 million tons, equivalent to a market size of 62.9 billion yuan.



2.3.1.2 Market demand driven by the 2025 commitment made by international brand signatories: 44 billion yuan

To corroborate the market size estimation, this section provides demand estimation of signatories of MacArthur Foundation for compostable materials by 2025 in accordance with signatories' commitment to the 2025 vision of ensuring 100% of plastic packaging to be reusable, recyclable or compostable[23]. The specific rationale of estimation is shown in the following:

Demand for compostable materials = (current plastic consumption volume-absolute committed reduction of plastic volume) × [100%-percentage of target recyclable plastics in 2025 (%)-percentage of reusable plastics (%)]

According to this deduction, it can be estimated that the demand volume of compostable materials disclosed by MacArthur Foundation signatories by 2025 will reach 12.57 million tons. PHA falls into the category of compostable materials. If PHA penetration can reach 10% in its target segment, then the demand volume can reach up to 1.25 million tons, equivalent to a market size of 44 billion yuan.

2.3.2 Medium-term PHA market (2030)

In medium-term, PHA will cost about 150,000 yuan/ton, and the predominant product segments by then will be plastic bags, plastic mulch and disposable cutlery. In total, the market size will stand at approximately 355.3 billion yuan.

2.3.2.1 Medium-term PHA market size: 355.3 billion yuan

Factoring in overall technical progress and diversified supply of feedstock, PHA cost is expected to reach 150,000 yuan/ton approximately in the medium-term, which is still higher than the cost of traditional plastics such as PP and PE. Therefore, product sales will be concentrated in product segments with strong demand for degradable plastics, such as plastic bags, plastic mulch and disposable cutlery, as well as part of the plastic packaging film segment excluding plastic bags. Among these segments, plastic bags are mainly produced from traditional plastics like LDPE and LLDPE, plastic mulch are mostly made of LLDPE, and disposable cutlery are primarily produced from PP.

In this section, plastic material demand in each of these product segments will be calculated based on the primary product segments mentioned above for PHA and then medium-term market size of the polymer family can be estimated. Various data estimations and hypothesis are shown in the below:

① The estimation is derived from the market size and consumption volume of plastic materials in each of these segments in 2020; among them the market size of global plastic bags is 22 billion yuan and market unit price is 10,000 yuan/ton; the consumption volume of global plastic mulch can be derived from China's consumption data of the product as China takes up 3/4 of its global consumption;

② Suppose the penetration of degradable plastics in product segments of plastic bags, plastic mulch, disposable cutlery and other plastic packaging film materials is 60%, 50%, 60% and 30% respectively;

③ It is expected that the added PHA ratio will be higher in plastic bag segment as PHAs are preferred flexible materials; while increased PHA addition in plastic mulch will drive up product price and the product is rather price-sensitive. Added PHA ratio in plastic bags, plastic mulch, disposable cutlery and other plastic packaging film materials is assumed to be 40%, 10%, 45% and 15% respectively;

④ In the medium-term market, PHA unit selling price will be 25,000 yuan/ton.

It is estimated that the market demand of PHA in the medium-term is 14.213 million tons, equivalent to a market size of 355.33 billion yuan.

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[23] ELLEN MACARTHUR FOUNDATION

2.3.3 Long-term PHA final market (2040)

It is estimated that the final price of PHA can fall to around 10,000 yuan per ton in the future. By then, PHA is poised to replace PP and PE as packaging materials. This final market size could go beyond 1.2 trillion yuan.

2.3.3.1 Cost decline: final cost at around 10,000 yuan/ton

PHA feedstock supply falls into the category of manufacturing sector and the share of feedstock cost to production cost is rather large, reaching up to 50%. Starting from perspective of feedstock selection and utilization, the future space for cost reduction primarily lies in the following aspects: ① Cut unit cost of carbon source, for instance, adoption of crude palm oil or the more affordable, homogenously treated gutter oil (recycled oil); ② Optimize production process, for instance, through fixation of CO2 to reduce fermentation heat, improvement of fermentation conversion rate and extraction yield, decline of unit energy consumption or storage conditions optimization by increasing the volume of loaded liquid in each fermentation tank.

Take PHA produced from palm oil as an example, palm oil consumption for each ton of PHA production can be controlled at 1.2 ton by modifying strains to improve fermentation conversion rate and extraction yield. Cost per ton of palm oil can be decreased to around 4,000 yuan /ton by building local oil refineries near the palm plantation. Through synergizing with effective optimization of manufacturing cost and unit labor cost in the context of production scale-up, PHA production cost per ton can fall to around 10,000 yuan, putting its cost level in the middle rank compared with the cost of other degradable materials.

Production cost (yuan/ton)	PBAT	PHA	PLA
Direct feedstock (auxiliary ingredients included)	7,030	4,234	8,750
Manufacturing cost	1,272	4,552	1,987
Direct labor cost	200	1,787	756
In total	**8,502**	**10,573**	**11,493**

Source: IPO prospectus of Zhejiang Hisun Biomaterials Co., Ltd, Bluepha and industry research reports, etc.

2.3.3.2 Final market size: exceeding 1.2 trillion yuan

In comparison, PHAs possess similar properties as the ones found in PP and PE plastics. Even though PHA cost is relatively high in the short-term, still it is hopeful that the cost can fall to around 10,000 yuan in the long-term, making its price 20% higher than that of the traditional PP and PE plastics. Still, PHA is expected to fully substitute PP and PE as the primary option for packaging purpose in a reasonably predicted final market considering its contribution to environment protection.

In this section, specific estimations will be provided for the final market size of PHA. To ensure reliable results, estimations will be reasoned in two ways.

- **Estimation rationale I:**

PHA will substitute PP and PE for packaging purpose in the final market. Global plastic consumption estimation for packaging use can be derived from the share of PP and PE in plastic for packaging use. The derived consumption volume of PP and PE for packaging purpose equates the market demand of PHA. Lastly, market size can be concluded based on PHA unit price in the final market.

- **Data hypothesis estimated in the following:**

① Considering that PP and PE plastic segments are relatively established, leaving small room for future growth. Therefore, market growth factors are ruled out in this section when estimating the final market size of PHA based on PP and PE segment size. The estimation is derived using global plastic output data in 2020;

② *National Geographic* identifies that packaging accounts the primary share of global plastic consumption, taking up 40% approximately;

③ As the predominant materials for plastic packaging, PP and PE adoption in the packaging segment is around 71%;

④ PHAs fully substitute PP and PE in packaging segment of the final market, namely, PHA market demand equals to the demand of PP and PE for packaging;

⑤ Unit price of PHA in the final market is 12,000 yuan/ton.

It can be estimated that the global plastic output for PP and PE packaging is about 104.228 million tons, and the final market size of PHA will reach 1.25074 billion yuan.

- **Estimation rationale II:**

In the final market, PHA will replace PP and PE for packaging purpose. PE is divided into three types: LDPE, LLDPE and HDPE. The usage of PP and PE for packaging purpose can be further broken down into the following segment-based usage: PP packaging, LDPE packaging, LLDPE packaging and HDPE packaging. The respective packaging consumption is equal to the product of material output and the proportion of corresponding materials used for packaging purpose, and the corresponding PP and PE consumption for packaging purpose can be derived by summing up the consumption in each segment, which equates the PHA market demand. Market size can then be obtained based on unit price of PHA in the final market.

- **Data hypothesis estimated in the following:**

① Same as the rationale I, estimation is based on the global market size of PP and PE subdivided materials in 2020;

② According to Plastic The Fact, among all PP materials, the proportion of packaging materials is 44%; among all HDPE, LDPE and LLDPE materials, the proportion of packaging materials is 60%, 70%, and 70% respectively;

③ The market unit price of PP is 10,000 yuan/ton; the market unit price of HDPE, LDPE and LLDPE is 10,000 yuan/ton, 12,500 yuan/ton and 9,400 yuan/ton respectively;

④ In the final market, PHA completely substitutes PP and PE for packaging purpose, that is, the market demand of PHA is equal to the demand for PP and PE for packaging purpose;

⑤ The unit price of PHA in the final market is 12,000 yuan/ton.

It is estimated that the global PP and PE demand for packaging segment is 103.517 million tons, and the PHA final market is 1.2422 billion yuan.

In conclusion, according to the two estimation rationales, the global demand for PHA exceeds 100 million tons, and the final market size is over 1.2 trillion yuan.

2.3.3.3 Abundant supply of biomass

In the long-term, the earth's biomass supply can meet the final market demand of PHA as its feedstock supply can be consistently sourced not only from vegetable oils, but also from second-generation carbon sources (straw, waste cooking oil) and third-generation carbon sources (methane, carbon dioxide).

Take palm oil as an example, in the long run, the feedstock consumption for per ton of PHA production in the future can be reduced to 1.2 ton, thanks to the technological progress and feedstock loss reduction. At the moment, the global oil palm growing area is about 19 million hectares, and the corresponding output for palm oil is 81 million tons approximately. As a consequence, the maximum converted output of PHA can reach 67.5 million tons, which can already generate a large supply in the market. In addition, corns can also be used as a source of feedstock via corn-glucose-PHA pathway. At present, the global corn production is 1.05 billion tons. Excluding corns for food use (11%), feed use (53%), biofuel and other uses (14%), 22% remains available for a corresponding maximum production of 42 million tons of PHA.

Straw recycling is the megatrend for sustainable agricultural development and about half of China's straw resources await to be utilized. Straw is primarily composed of cellulose and hemicellulose, which can be turned into glucose through hydrolysis, then the glucose can be used as feedstock to produce PHA. To produce 100 million tons of PHA, about 650 million tons of straws are needed, accounting for less than 20% of global straw output capacity. In this regard, the final market demand for PHA can be fully met.

In addition to biomass feedstocks, PHA can also be produced through fixation of inorganic carbon sources such as methane and carbon dioxide. Feedstock diversification in the future will reinforce supply reliability of PHA products. Different types of carbon sources and their characteristics are listed below, and the definition of carbon source by generation applies to all biomanufacturing processes.

Classification and characteristics of different carbon sources

Carbon source by generation	Types	Representative carbon sources	Characteristics
First-generation carbon sources	Traditional biomass	Corn starch, soybean oil, rapeseed oil	Accessible, reliable supply, partially resulting in reduced food reserve
Second-generation carbon sources	Non-food biomass	Straw, waste cooking oil, organic effluent and coffee grounds	Large supply potential, existing technical choke points and difficulties in recycling, without the concern for food reserve reduction
Third-generation carbon sources	Gaseous carbon sources	Methane, carbon dioxide and industrial exhaust	Enormous supply potential, existing technical choke points, better solution to carbon emission, additional energy supply may be required

3

PHA industry overview

Since the first commercial exploration in 1992, PHA industry has walked through a journey of three decades. In this chapter, a historical review of PHA industry will be provided and introduction of major PHA suppliers such as Kaneka, Danimer, CJ-Bio and Bluepha will be given. In addition, production, sales, types and applications of PHA as well as production difficulties will be explored here:

- The journey towards PHA industrialization is not without twists and turns, however, propelled by global polices momentum and its huge market prospect, quite a few PHA producers find it compelling to move production expansion up their corporate agendas.
- From the perspective of PHA production, mass conversion rate is higher for lipid-based feedstock than the glucose-based one. Taking palm oil and glucose as examples, currently, PHA produced from palm oil is more affordable. From the viewpoint of sales, PHA products price level is high due to prominent supply and demand capacity imbalance, but the price is expected to drop in the future along with commercial progress.
- In terms of PHA types, there are various products such as PHB, PHBV, PHBH and P34HB, each with its unique application scenario. Having said that, PHBH and P34HB show better overall properties among the polymer family.
- From the perspective of production difficulties, PHA mass production is encountered with challenges such as the presence of odor and color resulted from low product purity, and the primary difficulty lies in the separation of PHA from intracellular and extracellular impurities. Overcoming this difficulty will be one of the major development paths for PHA production technology.

3.1 PHA industry development history

The PHA industrialization journey is one punctuated with twists and turns. The beginning of commercialization effort was in 1992 when AstraZeneca hoped to build the first factory to mass produce PHA products. However, the factory project was forced to be discontinued since the production cost of PHA was as high as up to 8 to 10 dollars/kg (about 17 to 21 dollars/kg at current level, the equivalent of 118 to 146 yuan/kg), an order of magnitude higher than the cost of traditional plastics. But producers have never gave up their pursuits on PHA commercial experiments since PHA polymers possess excellent properties thanks to their bio-based, plastic-mimicking and degradable nature.

Over the past three decades, many companies from UK, US, Japan and China have made many attempts to mass produce PHA. Accompanied by progress in synthetic biotechnology, PHA producing strains with higher productivity have been developed, which greatly boosted PHA output and effectively slashed the polymer's production cost. Moreover, propelled by global policy momentum, PHA's market prospect becomes increasingly promising, compelling quite a few PHA producers to move up the agenda of production expansion.

Development journeys for part of the PHA manufacturers

Kaneka

Danimer Scientific

CJ-Bio

Tianjin Green Bio

Ningbo Tianan

Bluepha

Beginning of PHA R&D deployment

1990

1999

PHBV pilot scale completion

2000

Company was founded and became one of the largest PHBV producers

2002

PHBV production line went into official operation, with production capacity of 2,000 tons/year

2003

Company foundation

2006

PHA pilot-scale success

Purchased PHA intellectual property from Procter & Gamble

2007

Received 20 million dollars of investment from prominent firms including KPCB, DSM and Northern Light and official launched PHA factory project with 10,000 tons of production capacity. The project occupies an area of 66,000 m2 and boasts production capacity of 10,000 tons/year

2008

2009

Official operation of PHA started at the end of the year

Beginning of experimental scale production of PHBH, with annual production of 1,000 tons

2011

PHA commercial demonstration plant built

2014

Green Bio renamed into Jiangsu Lvsu (green plastics)

2016

Company foundation

Procured a fermentation factory in Kentucky and planned to rebuilt it into a PHA factory

2017

First-generation PHA process pilot scale production experiment

Kaneka invested 2.5 billion Japanese yen to lift PHBH production capacity of its Takasago factory from 1,000 tons/year to 5,000 tons/year

2018

Green Bio went into complete production halt

Kentucky factory phase I began construction, with an annual production capacity of 9,000 tons of PHA final product

2019

Official announcement on planned capacity expansion of 10,000 tons per year

Construction started for Pasuruan PHA plant, Indonesia

2020

Second generation PHA pipeline pilot scale production completed

Kentucky factory phase II went into operation, and time of construction was December 2020. Annual production capacity is about 29,400 tons of PHA final product

Rolled out PHACT™ marine-degradable plastic

2021

PHA super-factory broke ground in Yancheng, with designed capacity of 5,000 tonnes per annum, and operation expected by the end of 2022

2022

Pasuruan PHA plant went into operation, Indonesia

2023

Capacity expands to 25,000 tons/year

Site: Kaneka Takasago Production Base
Investment : approx. 15 billion yen
Capacity: 15,000 tons/year
Start of Operation: January 2024

2024

CJ plans to expand PHA production capacity to 65,000 tons by 2025 and 300,000 tons by 2030

2025

2026

Capacity expands to 75,000 tons/year

Continue to expand production capacity to the level of 10,000 to 20,000 tons

2030

3.2 Overview of major PHA producers

To better understand PHA industry dynamics, we organized profiles of producers with production capacity of over 5,000 tonnes per annum:

- **Kaneka**

Kaneka (カネカ) is a Japanese chemical manufacturing company founded by separating from the Kanegafuchi Spinning Company, Ltd. in 1949. The company's primary business covers chemical products, functional resin, foam resin, food, medical products, medical devices, electronic materials, solar cells, synthetic fibers, etc. PHA is a new material category for Kaneka, and the company began PHA R&D effort since 1990s and pulled off a pilot capacity scale of 1,000 tons per year for PHA production in 2011. At the end of 2019, Kaneka's PHA factory with capacity of 5,000 tons/year started operation.

- **Danimer**

Danimer Scientific was established in 2004, starting its business with PLA modification. In 2007, Danimer purchased PHA technology from Procter & Gamble, adding to its bioplastic platform. At present, the first and second phase of Danimer Kentucky plants have started operation, bringing the plant's final PHA product (products are modified materials, containing other compositions except PHA) capacity to 38,500 tons/year in total, and making it one of the largest PHA manufacturers in the world. In 2021, Danimer acquired Novomer in a bid to produce more diversified portfolio of PHA-based polymers.

- **CJ-Bio**

CJ-Bio is a division of CJ Group in South Korea, which comprises numerous businesses in four major industries, namely, food and service, biotechnology, logistics and new distribution, entertainment and media. CJ acquired PHA business from Metabolix in 2016 and launched CJ-Bio business division in 2019, starting its PHA development based on Metabolix's technology. In May 2022, CJ-Bio's first PHA plant has been officially put into operation in Pasuruan, Indonesia. The plant was designed to run at a capacity of 5,000 tonnes per annum.

- **RWDC**

RWDC Industries is a PHA producer founded by Roland Wee and Daniel Carraway in Singapore. Its founder Daniel Carraway is a former shareholder of Danimer. The company owns a 5,000-ton production module in Athens, Georgia, US and the construction of its 25,000-ton module is currently under way.

- **Bluepha**

Founded in October 2016, Beijing Bluepha Microbiology Technology Co., Ltd is a synthetic biotech company dedicated to molecular and material research and development. Bluepha's core members are from cutting-edge academic institutes such as Tsinghua University, Peking University, and Chinese Academy of Sciences, as well as from Fortune Global 500 corporations. Bluepha's primary product type on offer is PHBH, and the company's 5,000 tonnes per annum facility is about to complete construction and is expected to be put into operation at the end of 2022. Bluepha also plans to expand its production capacity of PHA to 75,000 tons per year by 2026.

Company names	Kaneka	Danimer	CJ-Bio	RWDC	Bluepha
Time of establishing PHA business	1992	2007	2016	2015	2016
Country	Japan	US	South Korea	US/Singapore	China
PHA products	PHBH	PHBH	P34HB,P4HB	PHBH composite	PHBH
Trade name	Green Planet	Nodax	Phact	Solon	Bluepha
Feedstock	Vegetable oil	Vegetable oil	sugar	Vegetable oil	Vegetable oil & sugar
Capacity (t/y)	5,000	19,700	5,000	5,000	5,000
Certification	FDA and EFSA Food Contact Certification, Japan BiomassPla Certification, TÜV OK biobased, OK industrial compost, OK home compost, Japan Industrial Compost Certification, BPI Compostable in Industrial Facilities, TÜV OK biodegradable Marine, OK biodegradable Freshwater, ISO 9001, RSPO (Raw Materials) Supply Chain Certification	FDA and EFSA Food Contact Certification, TÜV OK biodegradable Soil, OK biodegradable Fresh Water, OK biodegradable Marine, TÜV OK industrial compost, OK home compost and OK biobased	TÜV OK industrial compost, OK home compost, OK biodegradable Soil, OK biodegradable Freshwater, OK biobased, OWS OK biodegradable marine	FDA and EFSA Food Contact Certification, TÜV OK biobased, OK industrial compost, OK home compost, OK biodegradable Soil, OK biodegradable Marine and OK biodegradable Fresh Water	TÜV OK biobased, EFSA Food Contact Certification

*Production capacity refers to that of the virgin materials

Other overseas PHA producers with smaller capacity:

Company names	Bio-on	Full Cycle Bioplastics	Nafigate	Newlight Technologies	Biomer	Mango Materials
Time of establishing PHA business	2018	2014	2012	2003	1994	2012
Country	Italy	US	Czech Republic	US	Germany	US
PHA products	Mainly PHB and PHBV; others include PHA containing 4HV	P3HB and PHBV	P3HB	PHB	P(3HB), P(3HB-co3HV)	P(3HB)
Trade name	Minverv	-	Hydal	AirCarbon	Biomer	YOPP+
Feedstock	Sugar	Organic wastewater	Waste cooking oil & coffee grounds	CO2 and methane	-	Methane
Capacity(t/y)	Bankrupted	-	100-200	-	1,000	Pilot scale
Certification	TÜV OK biodegradable Fresh Water, USDA Certified Biobased Product	-	Marine Degradable Report, Brno University of Technology	Carbon negative: ISO 14046-3 PAS2050:2008/2011 FCN 1754 Food Contact Substance ASTM D6400 Industrial Compost ASTM D6691 Aerobic Biodegradation of Plastic Materials in Marine Environment	-	

Other domestic PHA producers with smaller capacity:

Company names	Ningbo Tianan	Tianjin Green Bio	ECOMANN	PhaBuilder	MedPHA	COFCO
Time of establishing PHA business	2000	2003	2008	2021	2019	2021*
Country	China	China	China	China	China	China
PHA products	PHB and PHBV(2%)	P34HB	P34HB	PHBH, P3HB4HB	P34HB, D3HB	PHBH, P34HB
Trade name	ENMAT	Greensol	Ecomann	-	Machgreen, Machnoon, Machloom	
Feedstock	Sugar	-	-	Sugar & vegetable oils	Sugar & vegetable oils	Sugar & vegetable oils
Capacity(t/y)	2,000	Bankrupted	-	1,000	1,000	1,000
Certification	EU REAC Certification BPI Certified Compostable, EU Food Contact Certification, TÜV OK biodegradable Marine		DIN CERTCO （Cert.No.:7 W0127）	-	-	-

3.3 PHA production cost and price

3.3.1 PHA production cost with different sources of feedstock

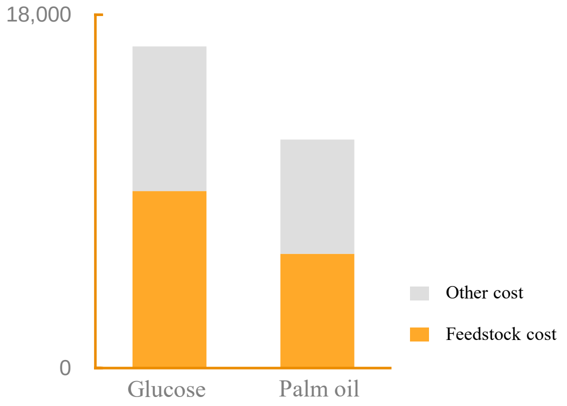
Generally speaking, feedstock production costs about half of PHA production cost. At present, the primary feedstocks for PHA production are vegetable oil and sugars. This section takes palm oil and glucose as an example to estimate related cost: in the next three to five years, PHA production cost will be around 30% higher than that of the PLA and selling price will be approximately 1.5 times of PLA.

- Theoretic mass conversion rate for glucose-based PHA production is 47.7%. In theory, to produce 1 ton of PHA, 2.1 tons of glucose are needed. Since the market unit price for the feedstock is 4,300 yuan per ton, therefore, PHA feedstock cost per ton can be calculated to be 9,015 yuan.
- Theoretic mass conversion rate for palm oil-based PHA production is 137.5%. In theory, to produce 1 ton of PHA, 0.73 ton of glucose are needed. Since the market unit price for the feedstock is 8,000 yuan per ton, therefore, PHA feedstock cost per ton can be calculated to be 5,839 yuan.

According to the above calculation, the feedstock cost per kg of palm oil-based PHA is 36% lower than that of the glucose-based PHA. The cost difference reflects different conversion rates between PHA synthesized with different feedstocks, while the conversion rate difference is determined by unique metabolic pathways of PHA synthesis with varied feedstocks. During glycolytic pathway, one third of carbon atoms of glucose will be removed (which becomes CO2), while there is no loss of carbon atoms for palm oil during β-oxidation pathway, therefore enabling a higher theoretical conversion rate. Despite the higher theoretic conversion rate of palm oil pathway compared with that of the glucose pathway, when it comes to specific production settings, the question of how high the conversion rate can be with which kind of feedstock will only be answered by the substrate bacterial strains and their modification capabilities.

Feedstock	**Glucose**	**Palm oil**
Metabolic pathways	Glycolysis	β-oxidation
Theoretical mass conversion rate	47.7%	137.5%
Feedstock cost	4,300 yuan/ton	8,000 yuan/tons
Theoretic cost per ton of feedstock	9,015 yuan	5,839 yuan
*Take PHB production as an example		

Theoretic cost limit of PHA production per ton (unit: yuan)



Source: feedstock unit consumption is based on theoretic conversion, and unit price is derived from the market

At present, frontrunners are exploring more sustainable feedstock routes, for instance, carbon dioxide and organic carbon sources can be used in combination as feedstock for PHA commercial production. Organic carbon sources are not only comprised of sugars and vegetable oils that we commonly see, but also include other categories of renewable sugar and oil, such as straw sugar, animal oil and gutter oil (recycled oil). In the future, PHA production efficiency and process sustainability will be continuously improved.

3.3.2 PHA selling price

Price interval per ton of PHA, PLA and PBAT are listed below. In the short-term, the emerging PHA sector will still be at its infancy of commercial development, and limited PHA supply will contribute to imbalance between supply and demand, leading to a high price level. In the future, supply capacity boost and production cost decline are expected along with commercial progress, enabling a substantial drop in PHA price.

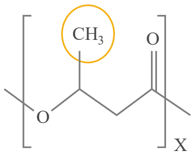
Types of Polymer	**Price interval per ton (yuan)**
PHA	50,000-80,000
PLA	22,000-24,000
PBAT	20,000-25,000

Source: Degradable Plastics Committee of China Plastics Processing Industry Association, Biodegradable Materials Research Institute

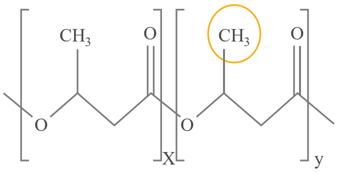
3.4 PHA product family and its application

3.4.1 PHA product family

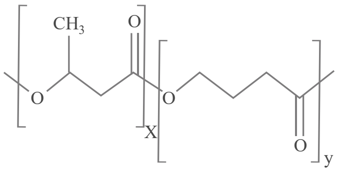
The most common types of PHA products available in the market are PHB, PHBV, P34HB and PHBH. Even though each of the polymers was introduced to the market at different times, there is no generational gap between them as each of these products possesses unique advantages in application.



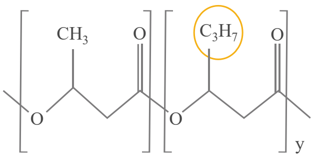
PHB（P3HB）



PHBV（P3HB3HV）



P34HB（P3HB4HB）



PHBH（P3HB3HH）

Note: major PHA products available in the market

- **PHB**

PHB is a short chain homopolymer of 3HB monomer, it is a stiff, crystalline polymer that can be used for injection moulding and fiber production. PHB is one of the earliest PHA products obtained in the process of commercial efforts. However, PHB thermally decomposes at temperatures in proximity to its melting point, resulting a short exposure for thermal processing. As a consequence, some producers tend to include a second monomer to improve the overall material performance. Currently, the US-based company Newlight manufactures PHB products like disposable cutlery, wallet and spectacle-frame.

- **PHBV**

PHBV is a medium chain crystalline co-polymer. The polymer is stiff and finds its application in injection moulding. Ningbo Tianan is a major PHBV producer, and the Netherland biopolymer company Helian Polymers sourced PHBV from Tianan as its primary material to develop suitcase that mimick properties of PP products. Besides, since PHBV is relatively brittle, it can be blended with amorphous PHA polymers like P4HB to tone down crystallinity to get materials with better compatibility.

- **P34HB**

P34HB is a short chain copolymer, and its crystallinity varies from crystalline to amorphous with the content of 4HB. When the content of 4HB monomer is between 5%-15%, P34HB will be crystalline; and when the 4HB content is between 15%-60%, the polymer will be non-crystalline; when the content of 4HB is at 60% and above, P34HB becomes crystalline again. The application of PLA in packaging is severely held back by the polymer’s inherent brittleness and weak ductility, and the limitation can be addressed by blending PLA with amorphous PHA such as P34HB (when 4HB>50%) to enhance blend polymer’s toughness. Currently, CJ Group from South Korea is working on amorphous P34HB production at commercial scale.

- **PHBH**

As a medium chain copolymer, PHBH’s crystallinity also varies from crystalline to amorphous with the content of HH. Crystalline PHBH offers in part both stiffness and toughness, and the polymer finds its application in products like coffee capsules. In addition, success has already been made by some producers in developing PHBH products such as disposable cutlery (fork, spoon and straw) and degradable plastic bags. When the content of HH is higher than 30%, PHBH becomes amorphous material. Bluepha is now proactively working on the development of amorphous PHBH with high content of HH.

3.4.2 Comparison of mechanical performance and processibility of different PHA polymers

In terms of physical property, PHBV and PHB are relatively high in mechanical strength and poor in toughness, and the two polymers are mostly employed in injection moulding and fiber-making; P34HB and PHBH polymers can obtain varying levels of strength and toughness thanks to their large latitude in content adjustment for the second monomer, the two polymers mostly find their application in blow moulding, plastic film casting, injection moulding and fiber-making.

In terms of processing property, the processing windows of PHBV and PHB are rather narrow, resulting a relatively poor or poor processibility; while PHBH and P34HB have revealed better processing property due to their wider processing window.

Property	PHBH, P34HB	PHBV	PHB
Strength	Adjustable	Relatively high	Relatively high
Toughness	Adjustable	Relatively poor	Relatively poor
Application	Blow moulding, film casting, injection moulding, fiber making	Injection moulding, fiber making	Injection moulding, fiber making
Processibility	Relatively good	Relatively poor	Poor

3.4.3 Comparison of the polymer patent ownership

When comparing the number of patent families of different PHA polymers in applications of packaging, thin film and disposable cutlery, a conclusion can be drawn that the number of patent families of PHBH and PHBV is significantly higher than that of the other PHA polymers.

When comparing the proportion of patent families of different polymers owned by overseas companies, a conclusion can be drawn that patent ownership in PHBV is relatively scattered, while the ownership landscape is relatively concentrated for PHBH. Among them, Kaneka takes up a whopping 66% share of the PHBH-based patent ownership.

	PHBH			PHBV			P34HB			PHB		
Number of patent families	155			184			42			92		
Share	32%			38%			8%			19%		
Ownership share of overseas companies	Kaneka	CJ	Danimer	Kaneka	CJ	Danimer	Kaneka	CJ	Danimer	Kaneka	CJ	Danimer
	66%	3%	0	15%	5%	0	33%	7%	0	7%	4%	0

Meanwhile, patent literature suggests that PHBH polymer is more competitive for the abovementioned applications in terms of mechanical property.

Product	Mechanical property		Patent literature reference
Thin film	Ductility	PHBH>PHBV>PHB	JP2006045365A US5254607A US7208535B2 JP2005162884A
	Aging rate	PHBH<PHBV	
Blow-molded products	Melt viscosity	PHBH<P34HB	JP2020122062A WO2019022008A1
	Shrinkage rate	PHBH<P34HB	
Disposable products	Ductility	PHBH>PHBV>PHB	JP2006045365A US5874040A
	Aging rate	PHBH<PHBV	

According to research findings, PHB is high in crystallinity, making it brittle and stiff, and extremely low in toughness; even though PHBV is a step up from PHB in brittleness, rapid aging rate of the two polymers makes them less competitive in making products like thin films. Consequently, PHBH's superior ductility compared with PHBV and PHB, and slower aging rate compared with PHBV, make the polymer very appealing in making products such as thin film and disposable products (reference: JP2006045365A, US5254607A, US7208535B2, JP2005162884A).

During blow molding process of bottles, pipes and rigid packaging, adjustment of reference indicators including resin melt viscosity and molding time is the key to increase production efficiency and quality; when it comes to selecting raw materials between PHBH and P34HB for blow-molding, PHBH's lower viscosity and shorter molding time compared with P34HB makes the former polymer more effective in avoiding adhesion to take place between blow-molded products, thereby boosting processing efficiency (reference: JP2020122062A, WO2019022008A1).

3.5 PHA polymer processing challenges

- **Slow progress in PHA recovery and extraction process**

Bioproduct production is comprised of upstream fermentation engineering and downstream recovery engineering. The former process is about providing a solution to bump up yields, while the latter focuses on ways to harvest product. Along with rapid technological development in synthetic biology, genetic editing and sequencing, strain development field has also witnessed substantial acceleration in technology iteration; the pace of fermentation design development and strain testing has also quickened as a result of increased fermentation throughput; nonetheless, the progress in recovery and extraction remains slow and R&D effort sluggish, holding back overall development of the synthetic bioindustry to a certain extent. Slow progress in separation and extraction process is one of the contributing factors to the inability of large-scale PHA production at the moment.

- **Difficulties in separation of intracellular PHA polymers from impurities**

Products of biological reaction consist of cells, extracellular metabolites, intracellular metabolites, residue substrate and mixed aqueous solution containing other components. Bio-based monomers of PLA and PBAT are in part extracellular products, therefore polymerization process and process for separation and purification of bio-based monomers both matter for these polymers as monomer purity is an immediate determinant for polymer purity.

Different from the above polymers, PHA belongs to intracellular products and completes polymerization within bacterial cells, leaving out 3-hydroxybutyric acid monomer production and in vitro polymerization. Moreover, along with development in synthetic biotechnology, bacteria have now extended their capacity from synthesizing simple PHB homopolymer to other homopolymers, short-chain, medium-and-long chain copolymers, and consequently, enabling PHA to have a broad range of mechanical properties and applications. Having said that, being an intracellular product also makes PHA separation and purification process more challenging. Put it another way, the new challenge lies in finding ways to effectively separate PHA from intracellular and extracellular impurities on the premise of allowable industrial conditions and reasonable cost input. Extracellular impurities, especially organic ones, may lead to a darker-colored product and release of unpleasant odor when thermally processed, thereby negatively influencing product quality. For decades, difficulty in separation process remains to be an unsolved puzzle for PHA researchers, thwarting efforts in PHA scale production.

- **PHA extraction and impurities removal**

PHA extraction process can be divided into organic-water solvent extraction systems and aqueous two-phase systems (ATPS) depending on types of solvents adopted. Among them, organic-water solvent extraction is basically no longer a feasible option due to its drawbacks including large solvent consumption, use of multiple solvents and great difficult in solvent recovery. Consequently, the predominant process adopted by major producers is ATPS, which covers a number of steps including cell disruption, enzymatic hydrolysis, solid-liquid separation and drying. Companies tend to develop their own extraction process depending on their upstream fermentation practices. For instance, downstream desalination step will be inevitable for producers adopting halophilic bacteria for PHA production.

PHA extraction process varies significantly between laboratory and industrial scale. On one hand, the methods used for solid-liquid separation are different. At laboratory scale, high speed centrifugation can be adopted for complete separation of solid-liquid phase, while at industrial scale, an industrial-grade separation device is commonly employed to enrich PHA, instead of performing solid/liquid separations. Therefore, extra steps of centrifugation and separation are needed, along with increased water consumption, to reach separation level at laboratory scale. On the other hand, way of drying differs between the two setting. At laboratory scale, simple batch-drying is commonly adopted, while continuous drying process is mostly opted in industrial production. Due to differences in PHA extraction in the two settings, it is difficult to apply laboratory results directly in industrial production, and more pilot-scale production experiments are required to further optimize process for industrial scale.

Similarly, it is challenging to reach laboratory level PHA impurities removal in scale production and PHA polymers produced tend to have color and odor if organic impurities are not effectively controlled in scale production. In order to cover up product defects, manufacturers may use various additives to obscure the color and odor in polymer granulation process. However, this approach does not provide a solution to the problem and will instead turn downstream manufacturers and consumers away with poor product experiences.

- **Examples of providing solutions to PHA production challenges**

Bluepha

Bluepha has developed a set of independent, proprietary extraction process with its proactive consolidation effort of the latest research progress in PHA field and years of independent innovation. Relying on these progress, the company provides solutions to issues like low recovery rate despite high PHA yield, low product quality and low degree of purity. In addition, Bluepha is able to keep this extraction process running on its exclusive pilot-scale digital platform all year round. As we speak, the extraction process is still in constant evolution at each and every technical indicator level.

Ningbo Tianan

Primary PHA products available from Tianan are PHB and PHBV, and the company possesses a capacity of around 1,500 tonnes per annum. In theory, bulk commodities tend to enjoy scale advantage in terms of cost, but the production scale of Tianan is still not large enough to reap this benefit. Having said, Tianan remains in the market for 20 years after its foundation as the company relies on its unique advantage obtained through the development of a low-cost, high-purity extraction process and niche application for its polymers. Among them, the extraction technology contributes the most to the company's success. In conclusion, finding a solution to address the choke points of polymer development is significant for PHA producers both in the short-term and long-term.

Tianjin Green Bio

Tianjin Green Bio also launched its PHA scale production effort, which ended up in failure. It can be learned that the failure may be attributed to lack of commercial readiness and technological sophistication. Among them, technology immaturity is mostly reflected in unreliable extraction process, as well as poor and inconsistent product quality.

Industry chain value: concentrates in midstream supply in the medium-to-short term

- **Sectors with value chains mimicking the one in PHA sector**

By observing industrial chains similar to the one in PHA sector, for example, petrochemicals (polyurethane-MDI), traditional plastic and degradable plastic (PBAT, PLA) sectors, conclusions can be drawn for the process of value migration in the above industrial chains; in the early period of industrial chain development, value concentrates in the midstream, and companies tend to form clusters and alliances, allowing them to have more bargain power for price negotiation with downstream clients; in the late stage, midstream companies will extend their value chain to the upstream sectors (“midstream and upstream”). By doing so, companies can ensure reliable supply of key feedstocks and thereby are able to maximize their value chain in the long run.

- **Value rationale of PHA industrial chain**

In the medium-to-short term, technology breakthroughs will provide commercial feasibility in terms of product quality and cost, and the key in this early stage is to further ensure reliability of product supply. Consequently, value of industrial chain is most reflected in the midstream production process in this stage; in the long-term, since feedstock costs more than half of product cost and there is limited room left for future technological iteration, therefore further cost reduction effort can only be achieved through integrated use of feedstocks. As a result, PHA producers will extend their value creation to the upstream to incorporate feedstock supply in the long run.

4.1 Define PHA industry chain

The upstream of the biodegradable plastic industry chain is feedstock production. Categorized by source of feedstocks, plastic can be divided into bio-based plastic and petroleum-based plastic. PHA falls into the category of biodegradable materials, and it differs from conventional petroleum-derived plastic in the upstream of the industrial chain. As a matter of fact, the upstream raw materials for traditional plastic sector are non-renewable resources, such as naphtha derived from crude oil process and steam cracked coal. While the upstream feedstock for PHA production adopts renewable biomass. The structure of biodegradable plastic industrial chain is shown in the following:

Upstream of the industrial chain

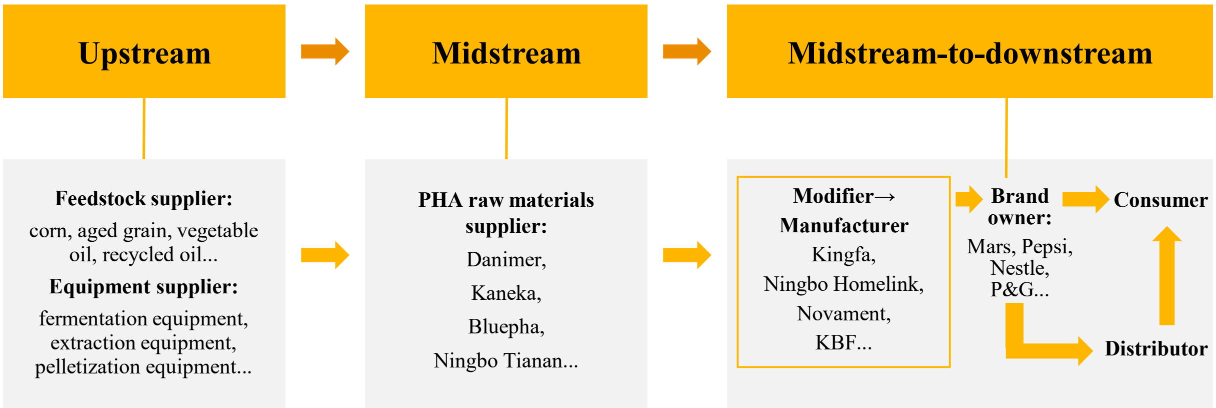
Companies in the upstream are mostly feedstock suppliers that provide various forms of renewable biomass (including sugars and lipids), and equipment suppliers that cover production processes including fermentation, extraction and granulation in the midstream.

Midstream of the industrial chain

Companies in the midstream are primarily PHA suppliers that perform microbial fermentation of upstream feedstocks and sell PHA raw materials (in powder or granule forms) to midstream and downstream clients after processes including extraction and pelletization. Representative companies are Kaneka from Japan, Danimer from US and CJ Group from South Korea.

Midstream-to-downstream of the industrial chain

Companies in the midstream-to-downstream of the industrial chain are mostly polymer modifiers, polymer manufacturers and brand owners. Among them, polymer modifiers will blend PHA raw materials with other auxiliary additives with the goal of improving a specific property or certain properties to meet production demand; polymer manufacturers will produce finished products directly from raw materials; brand owners will provide commercial products based on finished products, and sell them to downstream clients, eventually reaching consumer end.



Upstream → **Midstream** → **Midstream-to-downstream**

Feedstock supplier:
corn, aged grain, vegetable oil, recycled oil...
Equipment supplier:
fermentation equipment, extraction equipment, pelletization equipment...

→

PHA raw materials supplier:
Danimer,
Kaneka,
Bluepha,
Ningbo Tianan...

→

Modifier→
Manufacturer
Kingfa,
Ningbo Homelink,
Novament,
KBF...

→ **Brand owner:**
Mars, Pepsi, Nestle, P&G...

→ **Consumer**

Distributor

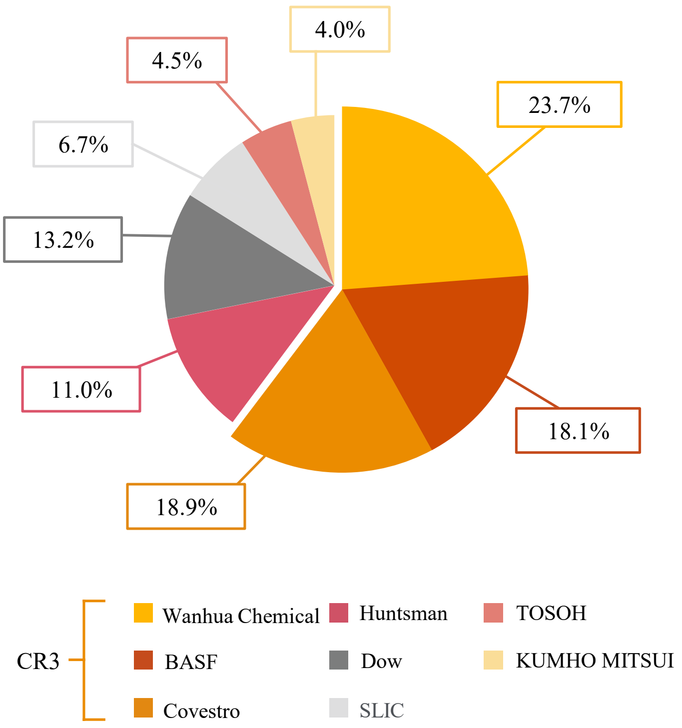
4.2 Value distribution of similar industry chains

- **Midstream and upstream markets are where the highest value of industrial chain lies in polyurethane (MDI) sector, and midstream producers will extend to both upstream and downstream in the long-term**

Industrial chain landscape: the overall trend in polyurethane (MDI) sector is that both midstream and upstream are dominated by a few frontrunner companies, and the downstream application segments are structurally diversified. In terms of capacity, CR5 penetrates 91% of the market in the midstream and upstream sectors[24], a few major manufacturers including Wanhua Chemical and Covestro dominate MDI supply in the midstream and upstream and possess absolute pricing power. Companies in the downstream are primarily manufacturers of various niche polyurethane products, such as flexible foams, rigid foams, and grouting materials. The market concentration ratio is relatively low and there is a vast number of manufacturers in the downstream sector, among which over 80% of them are small and medium-size enterprises (SMEs)[25]. In addition, applications downstream are relatively diverse, thereby manufacturers tend not to have much of a say in terms of pricing. For instance, the largest downstream application is construction materials, which only takes up 28.6% of the total polyurethane demand in the industrial chain[26].

Value migration process within the industrial chain: in the short-to-medium term, midstream producers owning MDI technology and production facilities tend to dominate the market and are privileged to set the market price. In the long-term, there is a tendency that midstream producers will extend to both upstream and downstream to cover the entire value chain, and further drive down cost.

Capacity distribution of global MDI producers in 2020

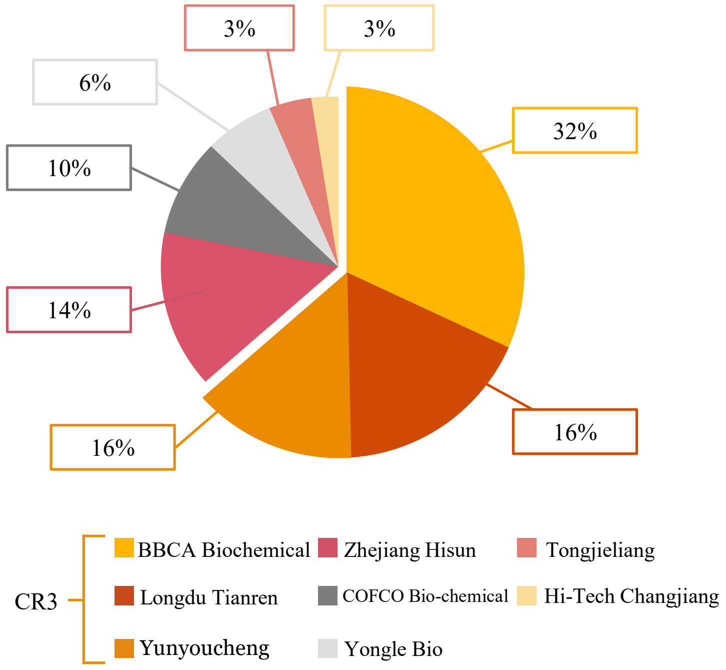


- **Midstream and upstream markets are where the highest value of industrial chain lies in traditional plastic sector, and value maximation can be achieved through midstream and upstream integration**

Industrial chain landscape: industrial concentration ratio is relatively high in midstream and upstream of conventional plastic industry in China, petrochemical and coal chemical producers are the major players in this market, among them large-scale petrochemical corporations supplied over 80% of the plastic materials in the market. Sinopec and PetroChina are the leaders in the petrochemical sector, accounting for over 60% of the market share. Due to their market dominance and strong pricing power, they receive the lion's share of profits in the sector. While the downstream is a relatively diverse market with various plastic fabricators offering an array of different products.

Value migration process within the industrial chain: since the market concentration ratio in the raw materials segment of the petrochemical industry is high in China, it becomes natural practice for midstream plastic producers to integrate with the upstream petroleum provider in traditional plastic industry. As a result, only those producers extending to the upstream market can maximize the value of the industrial chain.

Capacity distribution of domestic PLA producers in 2020



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[24]《万华化学报告（二）：解析 MDI 行业运行规律》， 行业研究报告

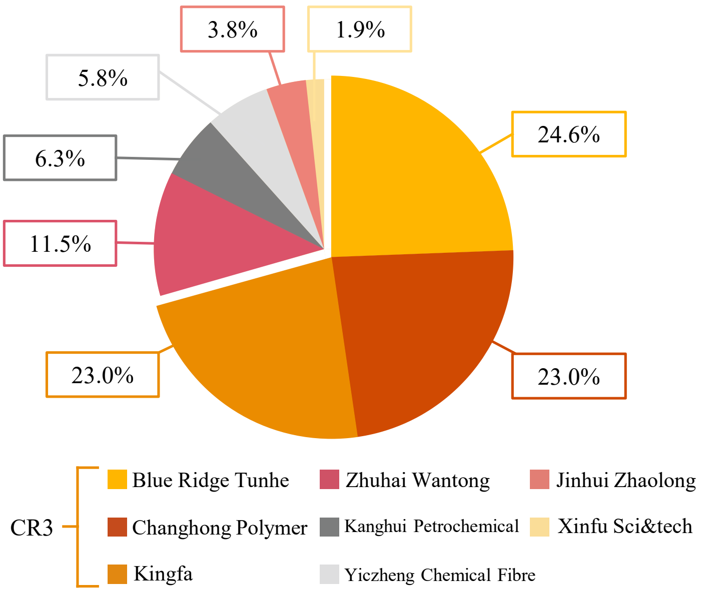
[25]《MDI 产业链梳理：供需格局如何？如何判断后期 MDI 价格？》， 行业研究报告

[26]《聚氨酯行业研究及万华化学深度解析》， 行业研究报告

• Midstream market is where the highest value of industrial chain lies in PLA sector in the medium-to-short term, and whole-industry-chain integration is an inevitable trend in the long-run

Industrial chain landscape: market concentration ratio of the PLA sector is relatively high, with CR3 taking up 64% of the market. Generally speaking, companies in the midstream and upstream are PLA producers, and those having the capacity to produce both lactide and PLA, as well as owning core production technology and equipments are the producers with better bargaining power. While the downstream market is quite fragmented, mainly comprised of medicine, packaging, and industrial application segments. Therefore, the bargaining power is relatively weak in the downstream market.

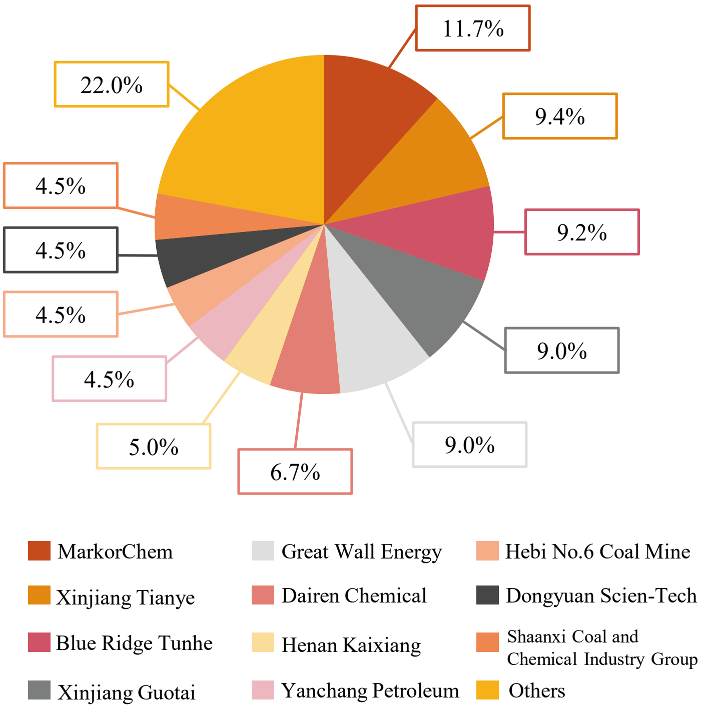
Value migration process within the industrial chain: midstream producers of lactide and PLA create the most value for the industrial chain in the medium-to-short term. In the long-term, value creation process in the industry will extend from midstream to integrate the upstream supply of lactic acid feedstock, and cost benefits generated from whole-industry-chain integration will become the core competitiveness for PLA producers.


Capacity distribution of domestic PBAT producers in 2021

• Midstream and upstream markets are where the highest value of industrial chain lies in PBAT sector

Industrial chain landscape: The market concentration ratio of PBAT industry is relatively high, and as of the end of 2021, frontrunner in this sector is Xinjiang Blue Ridge Tunhe Chemical Industry Joint Stock Co., Ltd, the company ranks number one in both domestic and overseas markets with its annual PBAT capacity of 128,000 tonnes per annum, contributing over 24% of China's PBAT capacity. The third largest producer Kingfa owns approximately 23% of domestic capacity, the equivalent of 120,000 tons of PBAT produced annually. While the downstream market doesn't have a strong bargaining power, and is primarily comprised of segments such plastic mulch, packaging and industrial application.

Value migration process within the industrial chain: Due to limited progress in capacity expansion of the upstream BDO feedstock, capacity crunch will remain to be an issue for midstream market of the industrial chain in the medium-to-short term. Therefore, industrial value chain will extend to PBAT's feedstock end (BDO) in the long-term. The ability to consolidate midstream and upstream markets will be telltale of a producer's core strength. At present, market frontrunner Blue Ridge Tunhe has already made its way into PBAT's midstream and upstream industrial chain. As a result, the company is better integrated vertically and well positioned to drive down production cost. In conclusion, preliminary vertical integration of midstream and upstream of PBAT sector has already taken place.


Capacity distribution of domestic BDO providers in 2020

In conclusion, industrial chain value distribution in petrochemical, traditional plastic and degradable sectors share a common shift pattern: at the earlier stage, industrial values are most generated in the midstream, and will extend upstream in the later stage to obtain maximum value in the long-term. In comparison, PHA industrial chain value also lies in the midstream manufacturing sector due to the significance of reliable product supply in the medium-to-short term. In the long run, manufacturers tend to integrate midstream and upstream markets due to relatively large share of feedstock cost. The value distribution rationale here is similar to the abovementioned sectors. In the following, an analysis on the current PHA industry development will be given and its future development path will be explored.

4.3 Value rationale of PHA industry chain

4.3.1 PHA Industry landscape

Since the number of producers with certain production scale is limited, the downstream of the PHA industry chain remains to be underdeveloped. A number of companies from countries including UK, US, Japan and China pursed great efforts to commercialize PHA production ever since 1992. However, production cost of PHA was significantly higher than that of the conventional petroleum-derived plastics. The uncertainties loomed large in the market, forcing some producers to opt out PHA product development. For instance, Procter & Gamble transferred its PHA technology to Meredian (the predecessor of Danimer) in 2006, and Metobalix sold its PHA pipeline to CJ in 2016. Over the past few years, PHA sector witnessed a rapid development and its production cost declined substantially since the application of CRISPR gene editing and other cutting-edge technologies. Having said that, only a few midstream producers boast the technological strength for scale production as the barrier to carry out large scale fermentation production is quite high. Hamstrung by limited number of producers with considerable production scale in the midstream, downstream market encounters with numerous constraints in development as there is not enough raw materials to be set aside for trial production.

4.3.2 PHA industry development trajectory projection

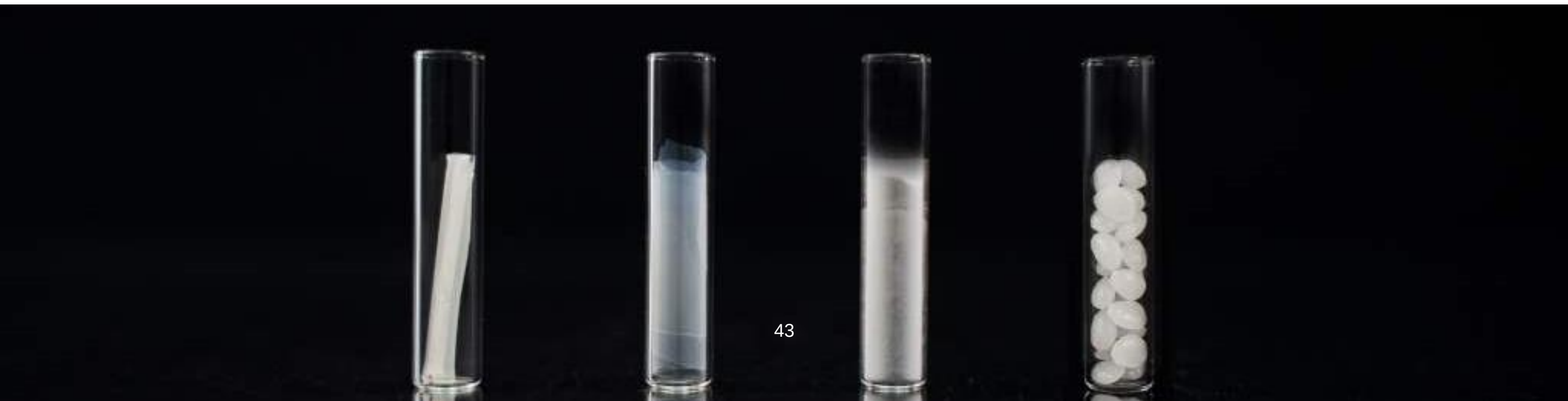
Since PHA polymers highly mimick materials such as plastic and degradable plastic in mechanical properties, application scope and industrial composition, therefore, the sector follows similar pattern in its industrial development trajectory in the long run. It can be reasonably argued that progress in process and technology will drive cost to its limit as the sector continues to grow. Producers in the midstream will be equally competitive in production technology by then and tend to opt for vertical integration of midstream and upstream to reduce cost. Therefore, PHA industry development can be roughly divided into the following two stages:

- **In the medium-to-short-term: frontrunners in scale expansion will be the firsts to profit from market in the condition of product commercial feasibility in both cost and quality**

Market demand for PHA polymers is evident in the medium-to-short term. Starting from market prospect unleased by plastic restriction orders of the domestic and the abroad, the initial PHA demand projection is 1.8 million tons based on estimation of its market penetration. While the existing capacity is less than 50,000 tons per annum, creating a sharp gap in demand. Having said that, the current PHA sector is still at its infancy relative to conventional plastic sector, meaning that the product cost is still relatively unaffordable; furthermore, product quality indicators such as color and odor are attributed to PHA fermentation and extraction, as well as separation of PHA from intracellular and extracellular impurities. Therefore, the precondition for producers to be the firsts to benefit from the market with preemptive strikes in scale production is to make product quality and cost commercially feasible through technological innovation. In the medium-to-short term, the core value of the PHA industry will be at the hands of PHA producers.

- **In the long-term: the key to stand out in the market is to build feedstock supply capacity to gain cost competitiveness**

In the long-term, there will be at least four PHA producers with production scale exceeding 300,000 tons per year. Producers will gradually start squeezing each other’s margin as the large profit margin at the early period of market development diminishes. At this stage, two types of companies will be able to stand out in competition, namely, companies adopting major process reforms and producers establishing their own feedstock supply capacity. Companies fall in these two categories are able to make their PHA products more cost-competitive, and consequently secure larger client base and squeeze competitors’ market share and profit margin. Over time, small producers will drop out of market competition one after another as they are unable to survive on thin margins for an extended period of time. This in turn leads to gradual increase of market concentration ratio in PHA sector. While after many rounds of price reduction, PHA will basically be on the same price level with PLA. As a result, it will increase PHA product demand and lower its demand elasticity. At the stage, the development sustainability of a company will significantly depend on whether scale production capacity and vertical integration of midstream and upstream are in place, and whether a company has reliable access to renewable biomass feedstocks. Eventually, the core value of the sector will gradually extend vertically from midstream to upstream.



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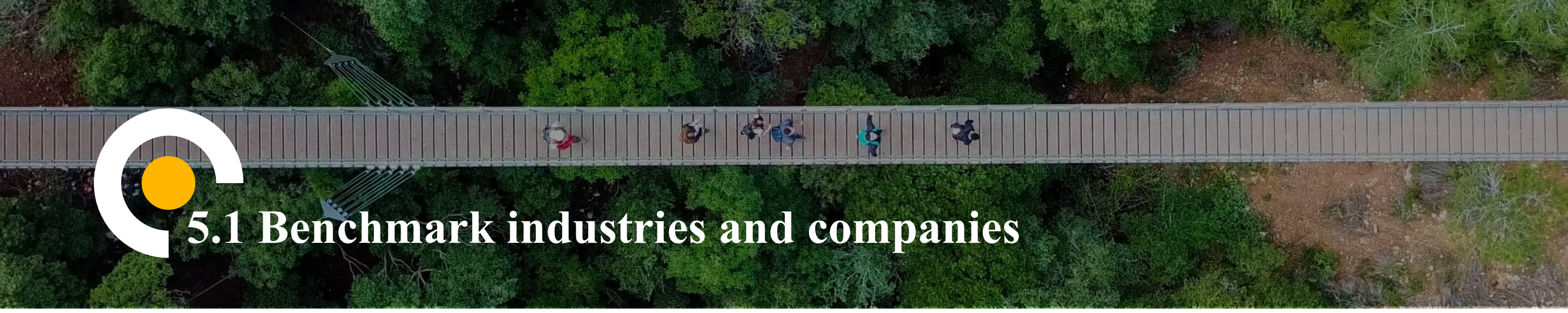
Eventual landscape:

Moving towards high levels of industrial concentration as market leaders emerge



5.1 Benchmark industries and companies

	MDI industry	PV industry	PVC industry
Relevance to the PHA industry	**Similar industry nature:** both sectors belong to the material industry, and their industry chain compositions are matched.	**Similar development path:** both sectors incorporate carbon neutrality policies to effectively reduce oil dependence; both sectors boost great market prospect and provide “better alternatives” under the current scheme.	**Similar industry nature:** both sectors belong to the material industry, and their industry chain compositions are matched.
Industry entry barriers	**High technical threshold:** the phosgene technology presents high-barrier for competitors and thus has led to an evident pattern of oligopoly market and a high long-term gross profit margin in the MDI industry. Liquid phase phosgene method, a key process of MDI production, consists of several steps including condensation reaction, photochemical reaction and separation reaction. It is not only technically challenging, but also requires effective control of the needed chlorine and toxic phosgene. Due to its extremely high threshold, there are only 5 companies capable to mass produce MDI in China presently.	**High technical threshold:** At the wafer level, as the epitome of technological transformation, PERC cell technology has lifted the conversion efficiency of P-type solar cells from less than 20% to nearly 23%. In 2020, the Ministry of Industry and Information Technology increased the standard of cell conversion efficiency to over 23%, further promoting the shift of P-type cells to N-type ones with higher efficiency (TOPCon and HJT technologies). Only companies with these core technologies can harvest the related development dividends.	**Low technical threshold:** PVC preparation technology was already established in China in 1980s.
	High threshold to scale up: Large investment amount and long production cycle. From the perspective of investment amount, the capital cost and maintenance cost of MDI production line are both high. From the perspective of production cycle, it takes at least 6 years (3 years for construction and 3 years from start of operation to production with full capacity) for the MDI production line to put into full production. Due to the toxic gas pollution and other issues during the production process, MDI facility construction projects are also required to pass environmental assessment and disclose the assessment result for two years.	**High threshold to scale up:** Large investment amount and long production cycle. From the perspective of investment amount, the silicon materials belong to heavy assets and require high capital investment, and the unit investment amount of its production line is up to RMB 0.8-1 billion per10,000 tons. From the perspective of production cycle, it takes 18 to 24 months to move from pilot scale silicon materials production to mass production, and it takes about 12 to 18 months to move from pilot scale wafer production to mass production.	**Low threshold to scale up:** Small investment amount and relatively dispersed industry structure.
Economy of scale effect	The MDI segment **boasts typical economy of scale effect** in the chemical industry, as a result, industry leaders can gain competitive edge on the cost front. As the production scale of MDI increases continuously, the utilization rate of raw and auxiliary materials will increase and the unit cost and unit depreciation will drop, ultimately drives down the production cost of MDI substantially.	The PV sector, especially the equation for silicon material and wafer, **has obvious scale effect**. Industry leaders can reduce the amortization of unit cost by expanding their production capacity, thereby growing market share and squeezing profit margins of their competitors. The higher the level of concentration, the higher the gross profit margin will be for companies.	PVC industry **does not have scale effects**. At present, the majority of products in the segment are highly homogenous and low-end PVC profiled bars. Most companies are small fabricators, with large but relatively dispersed production capacity. In addition, most PVC companies are constrained by geographical factors, resulting in low added value and profit for products, and limited production capacity and product property. There is relatively fierce industry competition in the same region.
CR5 in 2021	91%	87% for silicon raw materials, 84% for silicon wafer, 54% for cell wafer, 63% for PV modules	23%

Industry leaders	**A leading MDI company**	**A leading PV company**
	• Buttressed by technology reform, continuous capital investment and policy support, the company achieved rapid development from 2005 to 2010. Empowered by creative technical reform, the intermittent process of the MDI facility was eliminated, complete continuous production was realized in condensation, phosgenation and crystallization separation units, and utilities occupation and raw materials consumption achieved the same level as in overseas through energy integration and process optimization. • In terms of industry chain design, the company adopts the principle of "moving production activities to the upstream of the industry chain as much as possible", namely, the company aims to extend activities to the upstream to integrate industry chain and make MDI raw materials supply self-sufficient. Meanwhile, a thermal power plant has been set up for the production park to supply heat, steam, electricity and other production factors, further driving down the production cost. • With over two decades of development, the company gained 23% of the global MDI market in 2021, and its production capacity increased from less than 20,000 tons to 2.65 million tons, ranking first in the world.	• The founder of the company realized that the development path of the PV sector is to "achieve the lowest levelized cost of electricity (LCOE)" through research effort, therefore, opted for monocrystalline technology route, a route that is highest in investment cost and greatest in technical difficulty. With over a decade of dedication, the company emerged as the largest PV mono c-Si wafer fabricator in the world in 2011. • At the end of 2014, the company adopted a strategy to integrate industry, shifting from a professional mono c-Si wafer fabricator to an integrated solution provider. The integration strategy has enabled the company to generate profits from multiple building blocks of the industry chain (silicon wafers, cells, modules, etc.), therefore, avoiding downturn risk in a single market segment, reducing impact on module production costs arising from price fluctuation of each building block of production. The company's expenditure share is below the industry average, outperforming its competitors in comprehensive gross profit rate by 5% to 10%. • Since 2015, the company has vigorously advanced mono c-Si technology reforms, covering RCZ technology on the silicon rod end, diamond wire sawing technology on the wafer end, and PERC technology on the cell end. Consequently, multiple technologies formed a synergy, cutting costs and boosting efficiency for mono c-Si technology route. • In 2021, the global market share of the company's mono c-Si wafer and PV module product was about 43.6% and 22.7% respectively. Module reliability and consistent warranty contributed to enhanced brand recognition in the world. Meanwhile, the company has also built a global sales network over time to gain market share.

In general, MDI and PV industries require sophisticated R&D technologies, relatively large capital and equipment investment, and long production cycle in early stages. Only companies with certain financial and technical strength can stay competitive in the market. In the middle and later periods, with production scale-up of MDI and PV industries and iterative upgrade of production technologies, a few companies will stand out and be able to reduce cost and increase efficiency through integration strategy and grab market share, eventually become industry leaders. On the contrary, PVC industry has low market entry requirement and market competition is fierce, making it difficult for startups to grow into large corporations.

5.2 Underlying rationale for frontrunner companies to grow into large corporations in PHA sector

From analysis of sectors mimicking PHA, it can be concluded that PHA sector is conditioned for the emergence of industry leaders:

- **High requirement for market entry**

Capacity of mass production and technology development construct as barriers to enter the PHA sector. PHA is a sector requiring heavy assets, long cycle, and demanding requirement for mass production. Calculated from industry insider data of PHA sector, a construction capital expenditure of at least RMB 400 million is needed for every 10,000 tons of capacity. The available data suggest that it takes about 18 months to move from construction planning to actual production (excluding the ramp-up period), during which the actual revenue of the project is negligible. Companies without adequate cash flow to sustain periods when PHA building blocks all the way from production to sales are not in place will find it difficult to stay afloat.

PHA R&D chain is extensive, encompassing various disciplines and technical barriers to entry is high. Its R&D activities ranges from strain development, pilot-scale fermentation, extraction process development and optimization to mass production, requiring knowledge from over 20 disciplines (including but not limited to molecular biology, enzyme engineering science, metabonomics, proteomics, polymer materials science, engineering design, information and automation, etc.). At present, there are less than 5 companies capable of PHA mass production.

- **Long term technology iterations can lead to continuous cost reduction**

Compared with petrochemical industry, scale effect is less evident in PHA segment. However, PHA is a sector where cost can be continuously reduced through persistent technology iteration and accumulation. Raw materials cost, manufacturing cost, labor wages and depreciation are the major contributors to PHA production cost, of which raw materials take up over 50% of the production cost. The cost of raw materials can be effectively slashed through optimization of strain R&D process and increase in utilization and conversion rate of raw materials; in addition, raw materials cost can be reduced by industry chain upstream extension to integrate raw materials supply. While manufacturing cost can be effectively pruned through optimization of fermentation extraction process and rational engineering design.

In conclusion, the emerging biodegradable material sector shares similar building blocks as found in PV and MDI sectors. Therefore, PHA market tends to be highly monopolized by a few large corporations.

5.2.1 Building blocks to become a leader in PHA segment

PHA and degradable plastic industry at large are in an exponential development stage. By 2025, market demands production capacity of at least 20 million tons of degradable plastics. At the moment, commercial production capacity of PHA is less than 50,000 tons in the world, and it will take at least 3-5 years for new entrants to develop into commercial scale. To become a leader in the sector, a company must be ahead of new players in technology sophistication, capital strength and even speed for production expansion. **The period from now to 2027 is an important window for leading PHA companies to develop proprietary technologies, lower production costs, and sharpen competitive edges over competitors**.

A market leading should build the following four strength in competition. The first is to keep setting the pace in technology front by optimizing strain development process, improving utilization rate of raw materials, reducing production costs and building a reliable, high-quality product supply network; the second is to ensure competitiveness in terms of financial strength and organizational capacity, enabling rapid expansion of production scale; the third is to extend upstream of the industry chain to integrate production of raw materials and PHA, further expanding cost advantage; the fourth is to expand the downstream application of PHA to explore versatility of the polymer.

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[27]《原材料价格大幅涨价后，现在PBAT到底挣不挣钱？》， 行业研究报告

Appendix

- **Calculation formula and table details of medium and short-term market size:**
- **Calculation formulas:**

Consumption of plastic materials = Global market size/Unit market price of traditional plastic

PHA market demand = Consumption of plastic materials X Penetration of degradable plastic X Added amount of PHA

Short-term market size estimation	**Typical application**	**Plastic bags**	**Plastic mulch films**	**One-off cutlery**	**Other plastic films**	**Total (10,000t)**
	Main plastic material types	LDPE, LLDPE	LLDPE	PP		
Key assumption for plastic material consumption	Global market size (10,000 RMB)	15,180,660.0		36,539,888.0		
	Traditional plastic market unit price (yuan/t)	10,000.0		10,000.0		
Estimation of plastic material consumption	Plastic consumption (10,000 tons)	1,518.1	506.7	3,654.0	1,001.5	5,678.7
Key assumption for PHA market demand	Penetration of degradable plastic	30%	20%	30%	10%	
	Degradable plastic demand (10,000 tons)	455.4	101.3	1,096.2	100.2	1,652.9
	Added amount of PHA	2%	5%	15%	1%	
Estimation of PHA market demand	PHA market demand (10,000 tons)	9.1	5.1	164.4	1.0	179.6
Key assumption for PHA market size	PHA unit price (yuan/t)					35,000.0
Estimation of PHA market size	PHA market size (100 million RMB)					628.6

Note: The niche applications are not included in this estimation
Source: Statista, Grandviewresearch, Plasway, ScienceNet.cn, Sumibuy.com, IPO prospectus of Zhejiang Hisun, and industry research reports

Medium-term market size estimation	**Typical application**	**Plastic bags**	**Plastic mulch films**	**One-off cutlery**	**Other plastic films**	**Total (10,000t)**
	Main plastic material types	LDPE, LLDPE	LLDPE	PP		
Key assumption for plastic material consumption	Global market size (10,000 RMB)	15,180,660.0		36,539,888.0		
	Traditional plastic market unit price (yuan/t)	10,000.0		10,000.0		
Estimation of plastic material consumption	Plastic consumption (10,000 tons)	1,518.1	506.7	3,654.0	1,001.5	
Key assumption for PHA market demand	Penetration of degradable plastic	60%	50%	60%	30%	
	Degradable plastic demand (10,000 tons)	40%	10%	45%	15%	
	Added amount of PHA	364.3	25.3	986.6	45.1	1,421.3
Estimation of PHA market demand	PHA market demand (10,000 tons)					25,000.0
Key assumption for PHA market size	PHA unit price (yuan/t)					3,553.3

Note: The niche applications are not included in this estimation
Source: Statista, Grandviewresearch, Plasway, ScienceNet.cn, Sumibuy.com, IPO prospectus of Zhejiang Hisun, and industry research reports

- **Formula and table details of the final market estimation rationale I:**
- **Calculation formulas:**

Consumption of PP and PE packaging materials = Plastic output X Proportion of packaging use in plastic consumption X Proportion of PP and PE for packaging purpose

PHA market size = PHA market demand/PHA market unit price = PP and PE packaging material demand/PHA market unit price

	Item	**Data**
Key assumption for PP and PE packaging demand	Global plastic output (10000t)	36,700.0
	Proportion of packaging purpose in plastic consumption	40%
	Proportion of PP and PE for packaging purpose	71%
Estimation of PP and PE packaging demand	PP and PE packaging market demand (10,000t)	10,422.8
Key assumption for PHA final market	PHA final market unit price (RMB/t)	12,000.0
Estimation of PHA final market	PHA final market size (RMB 100 million)	12,507.4

Note: Niche applications are not included in this estimation
Sources: Statista, National Graphic, Plastics-the Fact 2019

- **Formula and table details of the final market estimation rationale II:**
- **Calculation formulas:**

Consumption of PP and PE packaging material = PP output X Proportion of output for packaging+
LDPE output X Proportion of LDPE for packaging+
LLDPE output X Proportion of LLDPE for packaging+
HDPE output × Proportion of HDPE for packaging

	Item	**PP**	**HDPE**	**LDPE**	**LLDPE**	**Total**
Key assumption for PP and PE packaging demand	Global market size (10,000 RMB)	79,950,860.0	47,928,237.0	20,649,138.6	37,624,005.0	
	Unit price (yuan/t)	10,000.0	10,000.0	12,500.0	9,400.0	
	Global market consumption (10,000 tons)	7,995.1	4,792.8	1,651.9	4,002.6	
	Proportion for packaging	44%	60%	70%	70%	
Estimation of PP and PE packaging demand	Consumption of PP and PE Packaging materials (10,000 tons)	3,517.8	2,875.7	1,156.4	2,801.8	10,351.7
Key assumption for PHA final market	PHA final market unit price (yuan/t)					12,000.0
Estimation of PHA final market	PHA final market amount (100 million RMB)					12,422.0

Note: Niche applications are not included in this estimation
Source: Grandviewresearch, Statista, Research and Markets, Plasway

Acknowledgement

Project supports

Dr. Teng LI, Co-founder and President of Bluepha

Dr. Haoqian ZHANG, Co-founder and CEO of Bluepha

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Important information

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