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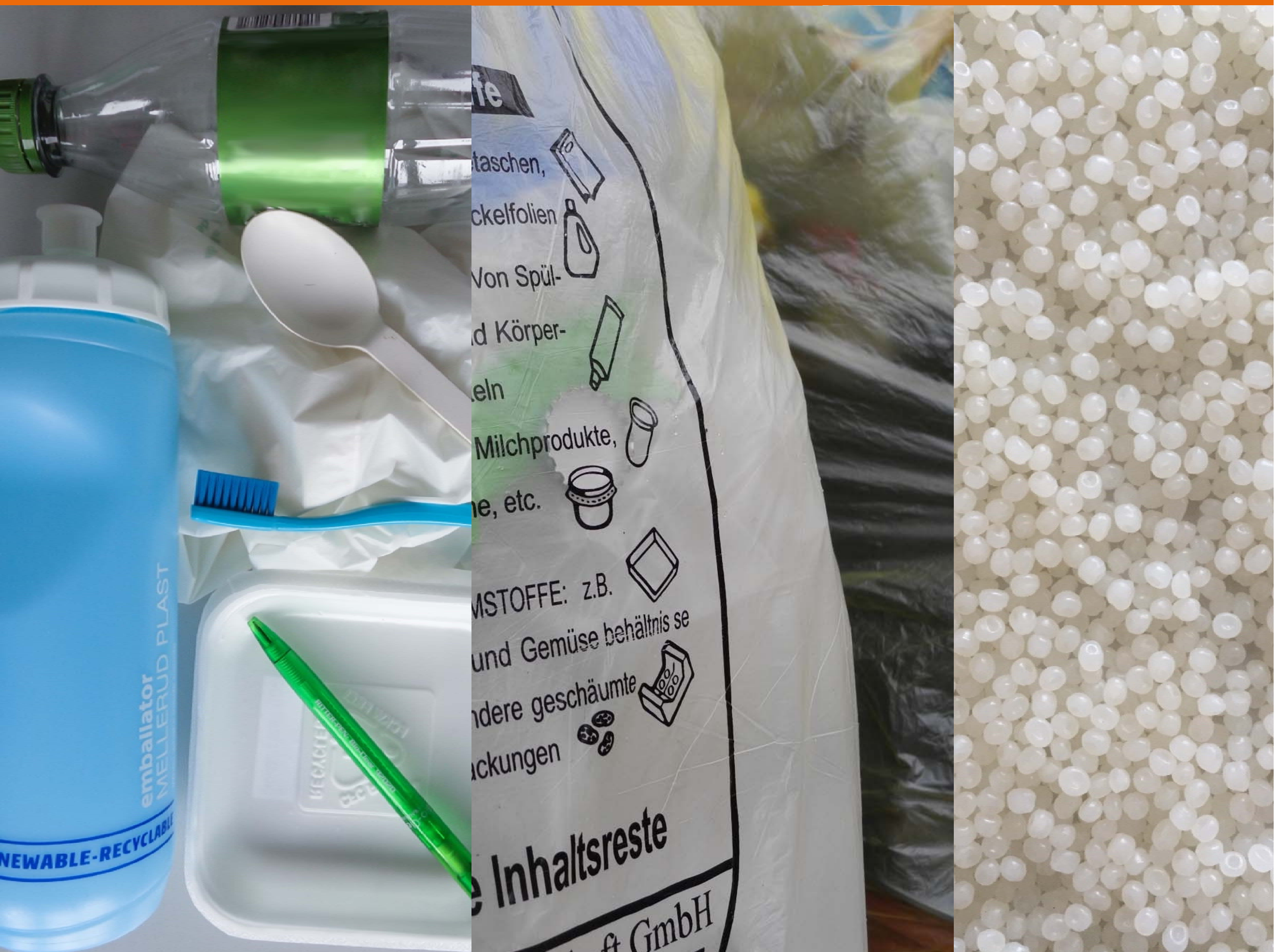
FRAUNHOFER UMSICHT TAKES POSITION
TOPIC: RECYCLING OF BIOPLASTICS



A POSITION PAPER OF THE SERIES »UMSICHT TAKES POSITION«

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FRAUNHOFER UMSICHT TAKES POSITION
OUR POSITION PAPERS

Within the series of position papers »Fraunhofer UMSICHT takes position« we cover issues which currently attract the attention of society, science and economy. In addition to our research activities, we would like to take a position and make a contribution towards greater objectivity in emotional debates. At the same time we would like to show whether and how we can help to solve societal challenges.

Our statements are developed within the staff of Fraunhofer UMSICHT. Each position paper is the result of an opinion-forming process throughout the institute; in this case driven by the Bio-Based Plastics department, which was supported by the Sustainability Group. In controversial issues, the staff of our institute often displays the diversity of opinions within the society. We openly present the variety of opinions in our position papers if we cannot come to one single position concerning the subject in question.

Please contact us:

For questions regarding the position paper about the recycling of bioplastics:

Bio-Based Plastics
Dr. Stephan Kabasci
+49 208 8598 - 1164
stephan.kabasci@umsicht.fraunhofer.de

For questions regarding our position papers in general:

Sustainability Management
Dr. Markus Hiebel
+49 208 8598 - 1181
markus.hiebel@umsicht.fraunhofer.de

Fraunhofer Institute for Environmental,
Safety, and Energy Technology UMSICHT
Osterfelder Strasse 3
46047 Oberhausen, Germany

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Picture credit front page: Fraunhofer UMSICHT, this picture shows products made of bioplastics on the left, a typical household collection bag with lightweight packaging in the center and the recovered regranulate on the right.

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FRAUNHOFER UMSICHT TAKES POSITION: TOPIC: RECYCLING OF BIOPLASTICS

Position of the Fraunhofer UMSICHT on the recycling of bioplastics

Background

Our way of life results in increased resource consumption and emissions [Welt-2016]. In order to achieve a sustainable development, it is imperative to bring about far-reaching changes in today's economic system and consumer behaviour. The United Nations has included these necessary changes in the Sustainable Development Goals in goal 12 »Ensure sustainable consumption and production patterns« [UN-2015]. For instance, sub-goal 12.5 calls for a substantial reduction in the amount of waste by 2030 through prevention, reduction, recycling and reuse [EDA-2017]. These demands are translated into concrete political strategies under the term »circular economy« [EC-2018a]. Goods and raw materials are to be recycled through intelligent product design (with re-use, extended use and recycling). This provides jobs and added value, especially locally (e. g. for repair) and ideally results in no more waste [UMSICHT-2017]. The EU takes up this concept in the circular economy package and plans to strengthen the implementation of the waste hierarchy. Furthermore, in January 2018, the European Commission published a strategy for plastics [EC-2018b]. An important driver of this strategy is the discussion about microplastics and marine littering, which Fraunhofer UMSICHT already addressed in an earlier position paper [UMSICHT-2015]. The topic of plastics was also discussed at the World Economic Forum 2018 in Davos. The European plastics association PlasticsEurope has issued a voluntary commitment to achieve high recovery and recycling quotas [EUWID-2018]. There are also voluntary commitments by some major companies such as packaging manufacturers, food companies and consumer goods manufacturers to increase the proportion of recycled materials in their products [EMF-2018; HVD-2017]. Incentives for recyclable packaging are set out in Section 21 of the German Packaging Act, which demands ecological structuring of the participation fees. Furthermore, according to Section 21 (1) 2, the use of recyclates and renewable raw materials is to be promoted [VerG-2017]. The law comes into force in 2019.

The following paper examines the material group of bioplastics in more detail and addresses the question of whether and how these bioplastics can contribute to closing circular material flows.

Bioplastics are either bio-based or biodegradable or both [EUBP-2017a], but other definitions are also in use[1] [FNR-2017; Vert-2012]. According to estimates by the European Bioplastics industry association, their worldwide production capacities will continue to increase in the coming years [EUBP-2017b], as they have done in the past. Bio-based, non-degradable plastics make up around half of all bioplastics. These are primarily so-called drop-in solutions which have the same chemical structure as fossil-based plastics already on the market, e. g. bio-polyethylene (bio-PE), bio-polyethylene terephthalate (bio-PET) and bio-polyamides (bio-PA). Today, most of the latter two types of plastic are offered as partially bio-based materials. Bio-PET for instance currently contains 20 percent bio-based carbon. Polyethylene furanoate (PEF), a plastic comparable to PET but completely bio-based with better barrier properties, will be added in future. Polylactic acid (PLA) and polyhydroyalkanoates (PHA) are the most common biodegradable bio-based plastics, additionally

[1] For an explanation of the terms, see the info box at the end of the document.

there are also biodegradable starch blends[2] containing up to 35 percent bio-based thermoplastic materials. Significant growth can be expected here especially in the PHAs, which after a long development period are now being commercially produced. The production capacities of PLA will also increase in the next five years [EUBP-2017a] and with Total Corbion, a second world-scale[3] competitor for PLA and lactide joins Natureworks in the market in 2018 [Corbion-2018].

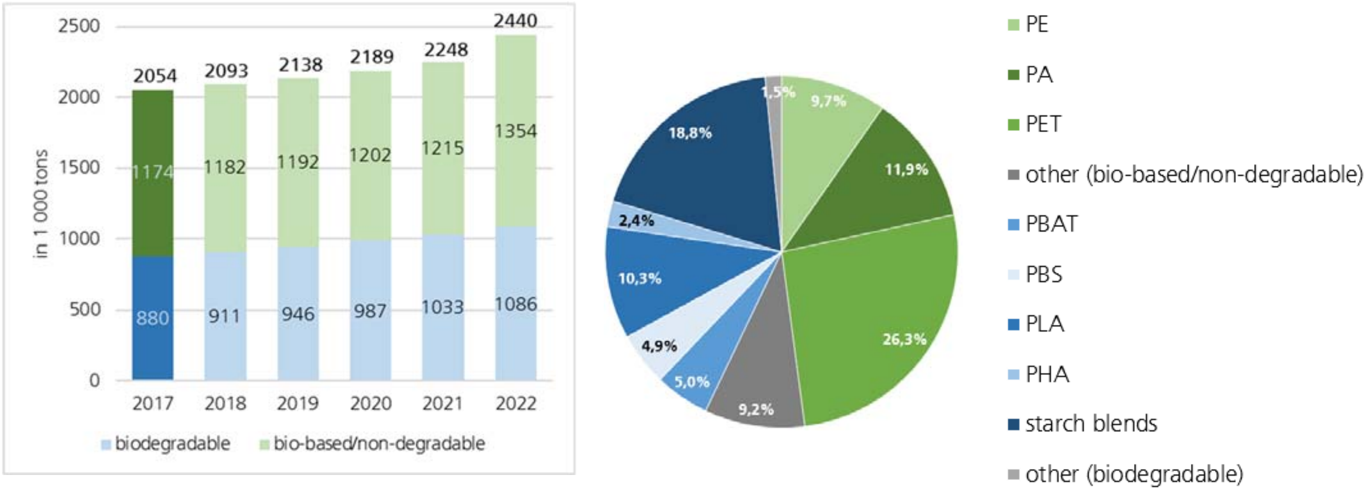


Figure 1: Worldwide production capacities for bioplastics, annual growth (2018-2022 forecast), production capacities 2017 by material type [EUBP-2017a], own presentation

So far, the share of bioplastics in the overall plastics market has been very low. 335 million tons of plastic were produced worldwide in 2016 [PE-2018]. Bioplastics account for about 0.6 percent of this, with the drop-in plastics Bio-PE and Bio-PET alone accounting for more than one third. Around 60 percent of bioplastics are used in packaging. This category also includes plastic bags for transporting fruit and vegetables, plastic carrier bags and waste collection bags. These product groups make up the majority of the market particularly in Italy and France, where their certified biodegradability (industrially compostable or home compostable) is required by law.

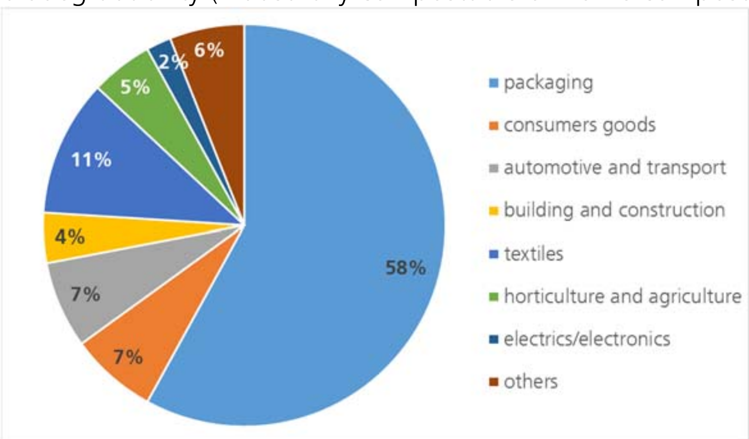


Figure 2: Worldwide production capacities for bioplastics 2017 by application [EUBP-2017a], own presentation

2 A plastic blend is a mixture of two or more different plastics.
3 World-scale plants are particularly economical production plants with very large capacities.

Other important applications are textiles, consumer goods, the automotive and transport sector as well as horticulture and landscaping [EUBP-2017a]. These wide-ranging applications are made possible by the multitude of different bioplastics with different properties. Additionally, customized polymer blends are often used to meet particular user requirements for the material. Bioplastics continue to be used mainly in niche markets. Large-volume individual applications in the packaging sector such as the Sant'Anna water bottle in Italy or the PlantBottle of the Coca Cola Company are exceptions.

Use is followed by disposal. This raises the question of the optimum disposal method for bioplastics, especially for short-lived products such as packaging.

The basic technical possibilities for the processing of plastic residual streams are extremely good due to the fast, contactless molecular recognition of plastic assemblies using spatially resolved near infrared spectroscopy[4] and the recognition of shape, colour and texture using digital image recognition and UV/VIS spectroscopy[5] [Visionsort-2006]. Newer methods using laser spectroscopy[6] and the method of hyperspectral imaging[7] have refined and extended the possibilities so that even black plastics - and these also according to plastic type -, glass and other materials can be detected [Beel-2017; Meyer-2017; Steinert-2016; TOMRA-oJ; Unisensor-2014; Unisensor-2016]. The possible spatial resolution of individual plastic residues on a sorting belt has also been further improved, so that sorting at flake level[8] is now state of the art. With the further development of the data analysis software of the optical sensors using self-adapting neuronal networks, a sorting task with regard to good and bad fractions can be solved in close proximity to the application. Even multilayer plastic composites can be detected at least in part using near-infrared spectroscopy [Axion-2016]. New developments such as electro-hydraulic comminution make the separation of galvanized plastics (metal-plastic composites) appear possible in the future [Herdegen-2016].

Like all conventional plastics, bio-based plastic residue streams can also be identified and sorted, as shown by studies commissioned by the Fachagentur Nachwachsende Rohstoffe e.V. (Agency for Renewable Resources) [Hiebel-2017] and the Deutsche Bundesstiftung Umwelt DBU (German Federal Environmental Foundation) [DBU-2015] using PLA and PLA-based blends as examples. The new bottle material based on polyethylene furanoate (PEF), which is currently being launched on the market and is even explicitly advertised as being recyclable via the existing process chains [SYNVINA-2017].

Limiting factors for sorting, and thus limiting the quality and quantity of individual sorting fractions, are at present primarily:

- technical-physical factors of the separation of the plastic waste to be sorted (e. g. the difficult special separation of flexible packaging materials or the detection of rolling packaging materials such as yoghurt cups),
- material design factors with regard to:

4 NIR spectroscopy: fast non-contact method that uses head radiation (NIR = near infrared radiation) to detect chemical structures of plastics.

5 UV/VIS spectroscopy: UV/VIS spectroscopy is a non-contact spectroscopic method belonging to optical molecular spectroscopy, which uses electromagnetic waves of ultraviolet (UV) and visible (VIS) light and makes it possible to detect the colour of plastics.

6 Laser spectroscopy: By using lasers, the energy density of the radiation interacting with the plastic can be increased to such an extent that atomic or molecular information is accessible.

7 Hyperspectral imaging is a method in which spatially resolved data are linked to wavelength-based spectroscopic data. The difference between multispectral and hyperspectral imaging lies in the number of detected points in the spectrum.

8 Flakes are shredded plastics.

  - composite materials (e. g. multi-layer composite films)
  - or material combinations (e. g. plastic with paper labels)

  and the associated increasingly complex evaluation of the data generated by sensors (especially with further individualisation of the design),
- economic factors that define the minimum content of a sorting fraction in the entire sorting stream (rising marginal costs when sorting to 100 percent purity), and
- resources requirement (energy and materials) to completely close cycles (e.g. sorting and processing effort).

With sufficiently pure sorting fractions, material combinations can also be largely separated through downstream processes, as shown by the separation of PET bottles into caps and PET flakes and the colour sorting of the PET flakes. Generally, complex sorting tasks can be carried out more easily the more unambiguous the material (e. g. PET) or the origin (e. g. bottle return systems). However, sorting mixed residual material streams from recycling bins or the Gelber Sack recycling scheme is the most difficult task in the area of packaging waste.

Economic factors ultimately dominate the quality (purity) of a sorting fraction. Due to the low volume, new types of plastics often cannot be sorted economically as a separate fraction and are either discharged for disposal or can contaminate other fractions. However, the influence of bio-based plastics as impurities is generally not greater than that of fossil-based impurities already present, as shown at Wageningen University [Oever-2017].

New plastics, whether bio-based or not, should therefore be considered holistically. Only a few new developments have been made in the field of plastics in the last 30 years, as the material properties and costs of the plastics developed beforehand have been greatly improved through a deeper knowledge of the physics and chemistry of polymers and innovations in processing technology. Aside from the fossil-based PA 46, several structurally new bio-based polymers are now available on a large industrial scale or will be available shortly. These include PLA, PEF, PHA and partially bio-based polyamides. Although not all partially bio-based polyamides can be considered new plastics from a historical perspective, they are now being appreciated in a new way from the point of view of sustainable added value, as is bio-based polyethylene. Developments in the field of climate protection, which make it necessary to turn away from the fossil fuel economy, as well as the needs of a growing world population and its aspiration to achieve prosperity, result in an increasing global per capita plastic consumption and the need for more climate-neutral raw materials (raw material shift). It is therefore to be expected that long-term efforts towards more recyclable plastics will be necessary if the raw material basis changes. Drop-in materials such as bio-based polyethylene can contribute to solving the climate problem. However, as polyolefins, which are particularly difficult to degrade, pose a major problem if they are not disposed of properly due to their longevity in the environment, overarching criteria must also be considered.

The new German Packaging Act therefore stipulates in Section 16 the gradual increase in the recovery of plastic waste to 90 percent by 2022, 70 percent of which must be recycled [VerG-2017]. The status quo of current recovery with its high proportion of energy recovery paths [Consultic-2016] will no longer be sustainable in future. Frans Timmermans, Vice-President of the European Commission is now putting pressure on industry: »Our whole economy needs to be transformed. We want to ensure that all packaging in Europe is recyclable in 2030« [Zeit-2018].

The increased use of bioplastics and the sorting of plastic waste must therefore be seen in the context of the entire economic value chain as well as in the context of the ecological effects, and requires national and international solutions.

Position of Fraunhofer UMSICHT

1. All plastic products, including those made of biodegradable plastics, are to be fed into a target-oriented waste management system. The littering of the environment with plastics, whether fossil-based or bio-based, degradable or non-degradable plastics, is a social and regulatory problem. Communication within society about the correct or incorrect handling of plastics - and in a broader sense the handling of all resources - at the end of their utilisation phase needs to be fundamentally intensified.

2. Multiple use, repairability and improved end-of-life management should be endeavoured for all types of plastic products, including those made of bioplastics.

3. Products and materials must be designed as far as possible in a way that allows them to be recycled. The range of plastics used today and the use of multilayer composites, especially for short-lived products such as packaging, must therefore be reconsidered. Material combinations that are difficult to recycle should be avoided. These include, for example:

   - material mixtures (e. g. PET with PA barrier layers)
   - metal-plastic combinations (such as aluminium as barrier layer)
   - plastic-paper combinations (e. g. through non-removable labels)
   - material combinations that are difficult to detect (due to product design)

   Other design criteria for recyclability are the ability of the packaging to be emptied of residues and residue-free separable components (e. g. lids for yoghurt cups). From 2019, recyclability will affect the fees for packaging that must be registered in the German recycling system (Section 21 VerpackG) [VerG-2017].

4. Materials with very good barrier properties are often used for food packaging. More intensive research is needed on how these solutions can be achieved without multilayer composites.

5. The use of renewable raw materials is an important strategic route due to the inevitable long-term move away from fossil raw materials and should certainly be adhered to, regardless of biodegradability. Another long-term option could be the material use of carbon dioxide powered by renewable energies [Marzi-2017].

6. Deposit solutions, e. g. for PET bottles, lead to high return rates (94 percent) at high purity and recycling rates [PET-2016]. An expansion of the deposit system to other materials should be considered openly and transparently with all stakeholders, taking into account the costs and benefits. New deposit systems based on bio-based plastics from the outset could increase market penetration.

7. Plastic packaging captured via the dual waste management systems can be identified and sorted using modern sorting systems. Optimized operational management makes it possible to achieve high sorting qualities (appropriate loading and belt speed). Even if the quantities of bioplastics are currently still small, sorting tests should be carried out with real products. This allows to optimize system design and the adaptive algorithms of software-controlled plastic detection in the event that larger quantities of bioplastics are included in the sorting process in the future.

8. Clear material identification beyond the chemical basis is helpful for better sorting. This can be achieved using barcodes, photo recognition or even marking additives [Nonclercq-2016]. These options should be pursued further.

9. Bioplastics currently account for well under one percent of plastic waste [Schwede-2018]. The purity requirements for the sorting fractions, e. g. by Der Grüne Punkt - Duales System Deutschland GmbH (DSD), allow far higher impurities. Studies have shown that hardly any deterioration due to the low bioplastics content in properties of post-consumer recyclates is noticeable in the sorting fraction [Hiebel-2017; Oever-2017]. It would be prudent to conduct further investigations here.
10. The aim must be to increase the proportion of recycled content in virgin material without causing pollutant carry-over. The use of recycled material in food contact is strictly regulated by the European Regulation EC 282/2008. The regulation stipulates that only recyclates whose production is quality-monitored and whose raw material basis has food approval are used [EK-2008]. Meaningful solutions must be found for all sides here and it must be assessed within which ranges recyclates can be used reasonably (consideration of expenditures and benefits).
11. Fraunhofer UMSICHT is of the opinion that labelling of recycled products (e. g. on recycling content and quality) is desirable and enables consumers to adapt their purchasing behaviour. For example, the RAL Quality Assurance Association Recyclates from recyclables from kerbside collection was founded by DSD and partners for this purpose. This aims to make the source of the raw materials visible [DSD-2018].
12. Biodegradable bioplastics should be clearly labelled. Biodegradable plastics in which initial degradation may occur due to contact with impurities or technical processes should not be used in applications that end up in the Gelbe Tonne or Gelber Sack recycling scheme at the end of their product life. On the other hand, it is necessary to adapt regulatory requirements (e. g. Biowaste Ordinance, Fertilizer Ordinance, municipal waste statutes) to open up the disposal route of composting of biodegradable products where it makes sense. One example of this is the biodegradable collection bag for biowaste.
13. So-called drop-in materials, which are bio-based plastics that are chemically identical to plastics from fossil raw materials, behave during recycling like their petrochemical counterparts and should be recycled together with these. Support through the incentive systems according to Section 21 of the new Packaging Act is considered sensible.
14. Life cycle assessments often do not provide a longer-term perspective [Finkbeiner-2014]. For example, they fail to consider that the production of natural gas and crude oil is becoming increasingly complex. Furthermore, life cycle assessments currently take no account of risks in crude oil production such as oil spills (tanker accidents, Deep Water Horizon) or leaks in gas or oil pipelines. An update of data sets for oil extraction is therefore imperative.
15. Fraunhofer UMSICHT recommends a comprehensive sustainability assessment for the evaluation of bioplastics. The balancing of economic and ecological criteria should increasingly be seen in the overall context of raw material supply, environmental services and ecological effects as a responsibility for society as a whole. The cycles of new materials are in theory no worse than the technically and economically (economy of scale) optimised cycles of established recyclables.

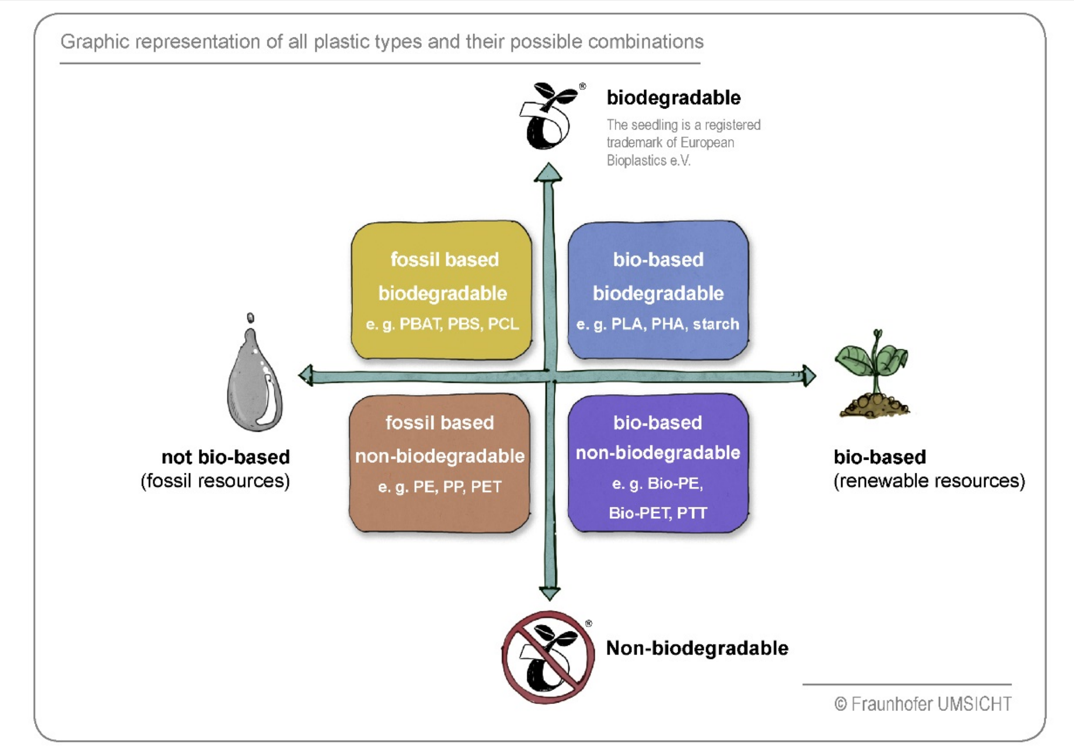
These facts and recommendations form the basis for technical and social innovations in the field of bioplastics that are being developed at Fraunhofer UMSICHT.

Bioplastics are biodegradable, bio-based or both

Bio-based means that the material or product has been (partially) produced from biomass, e. g. corn, sugar cane or cellulose. Fossil raw material sources remain (partially) untouched, local sources of added value secure jobs. Certification systems essentially evaluate bio-based plastics according to the content of »old« (fossil) and »new« (renewable) carbon. Manufacturers' data can be verified by means of physical procedures.

The term biodegradable describes a biochemical process in which microorganisms present in the environment convert the material into natural substances such as water, carbon dioxide and microbial biomass. Biodegradability is therefore not a function of the origin of the material, but is only related to its molecular structure. The process of biodegradation also depends on environmental conditions (e. g. humidity or temperature) and product design (e. g. thickness of the component).

This distinction is illustrated by a simple two-axis model into which all types of plastic and possible combinations can be classified:



The vertical axis shows the biodegradability of plastics, which must be demonstrated by standardised testing and certification procedures and is therefore a material property, while the horizontal axis shows the origin of the material, i. e. petrochemical or renewable raw materials.

Four possible groups can be derived from this scheme:

1. Non-biodegradable plastics from petrochemical raw materials - this category includes what is known as classical or traditional plastics.

2. Biodegradable plastics from renewable raw materials - plastics made from raw materials containing biomass and showing the property of biodegradability. These plastics are used, for example, in mulch films or biowaste bags.

3. Biodegradable plastics from fossil raw materials - plastics that are biodegradable but are made from fossil raw materials. The applications are comparable to applications in group 2.

4. Non-biodegradable plastics made from renewable raw materials - plastics produced from biomass but not biodegradable. These plastics are often so-called drop-in solutions, i. e. plastics that are chemically identical to those made from fossil raw materials (e. g. bio PE in cosmetic packaging).

Occasionally one also encounters the term »biocompatible«. This is used in connection with the compatibility of plastics in human or animal tissue. Biocompatible plastics degrade after operations without toxic intermediate and end products or are not attacked as foreign bodies by the immune system.

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References

[Axion-2016] McKinlay, R.; Morrish, L. (2016): REFLEX PROJECT: A summary report on the results and findings from the REFLEX project. Last time checked: 2018, April 4. http://www.reflexproject.co.uk/wp-content/uploads/2016/12/REFLEX-Summary-report.-Final-report.pdf

[Beel-2017] Beel, H. (2017): Sortierung von schwarzen Kunststoffen mit Hyperspectral-Imaging-Technologie, 10, p. 175–192. Neuruppin: TK Verlag (Recycling und Rohstoffe, 10). Last time checked: 2018, April 20. http://www.vivis.de/phocadownload/Download/2017_rur/2017_RuR_175-192_Beel.pdf

[Consultic-2016] Consultic Marketing & Industrieberatung GmbH (2016): Produktion, Verarbeitung und Verwertung von Kunststoffen in Deutschland 2015: - Kurzfassung -. Last time checked: 2018, April 9. http://www.bkv-gmbh.de/fileadmin/documents/Studien/Consultic_2015__23.09.2016__Kurzfassung.pdf

[Corbion-2018] Total Corbion (2018): Total Corbion PLA announces successful start-up of pilot plant in Rayong, Thailand. Pressemitteilung. Last time checked: 2018, April 5. http://www.biobasedeconomy.nl/wp-content/uploads/2018/03/PR-Total-Corbion-PLA-announces-successful-start-up-of-pilot-plant-in-Rayong-Thailand-180315.pdf

[DBU-2015] IG KURIS Interessengemeinschaft Kunststoffrecyclinginitiative Sachsen e.V. (2015): Verträglichkeit von biologisch abbaubaren Biokunststoffen mit den etablierten Systemen zur Erfassung und zum Recycling von Altkunststoffen. Osnabrück. Last time checked: 2018, April 9. https://www.dbu.de/projekt_31428/01_db_2409.html; Abschlussbericht wird in Kürze eingestellt

[DSD-2018] DSD – Duales System Holding GmbH & Co. KG (11.04.2018): RAL-Gütezeichen für Post-Consumer-Rezyklate. Last time checked: 2018, June 12. https://www.gruener-punkt.de/de/kommunikation/news/artikel/details/ral-guetezeichen-fuer-post-consumer-rezyklate.html

[EC-2018a] European Commission (2018): Towards a circular economy. Last time checked: 2018, March 6. https://ec.europa.eu/commission/priorities/jobs-growth-and-investment/towards-circular-economy_de

[EC-2018b] Abele, K.; Bethke, L. (2018): Kommission legt europäische Plastikstrategie vor. Last time checked: 2018, April 9. https://ec.europa.eu/germany/news/20180116-plastikstrategie_de

[EDA-2017] Eidgenössisches Departement für auswärtige Angelegenheiten EDA (2017): Agenda 2030 für nachhaltige Entwicklung: Ziel 12: Für nachhaltige Konsum- und Produktionsmuster sorgen. Last time checked: 2018, April 9. https://www.eda.admin.ch/agenda2030/de/home/agenda-2030/die-17-ziele-fuer-eine-nachhaltige-entwicklung/ziel-12-fuer-nachhaltige-konsum-und-produktionsmuster-sorgen.html

[EK-2008]	Europäische Kommission (2008): VERORDNUNG (EG) Nr. 282/2008 DER KOMMISSION vom 27. März 2008 über Materialien und Gegenstände aus recyceltem Kunststoff, die dazu bestimmt sind, mit Lebensmitteln in Berührung zu kommen, und zur Änderung der Verordnung (EG) Nr. 2023/2006. Last time checked: 2018, April 10. https://www.verbrauchergesundheit.gv.at/dateien/lebensmittel/rechtstexte/lm_recht_eu_kontaktmaterialien_vo_282-2008.pdf?63y0e5
[EMF-2018]	Ellen MacArthur Foundation (2018): 11 companies take major step towards a New Plastics Economy: 11 leading brands, retailers, and packaging companies work towards 100% reusable, recyclable or compostable packaging by 2025 or earlier. Last time checked: 2018, April 9. https://newplasticseconomy.org/news/11-companies-commit-to-100-reusable-recyclable-or-compostable-packaging-by-2025
[EUBP-2017a]	European Bioplastics (2017): Bioplastics market data. Last time checked: 05.04.2018. http://www.european-bioplastics.org/market/
[EUBP-2017b]	European Bioplastics (2017): Weltweite Produktionskapazitäten für Biokunststoffe steigen um 20 Prozent. Pressemitteilung. Last time checked: 2018, April 5. http://docs.european-bioplastics.org/PR/2017/EUBP_PM_Weltweite_Produktionskapazitäten_Biokunststoffe_steigen_um_20_Prozent_171129.pdf
[EUWID-2018]	EUWID Recycling und Entsorgung (2018): Europas Kunststofferzeuger mit freiwilliger Selbstverpflichtung: https://www.euwid-recycling.de/news/international/einzelansicht/Artikel/europas-kunststofferzeuger-mit-freiwilliger-selbstverpflichtung.html. Last time checked: 2018, April 20. https://www.euwid-recycling.de/news/international/einzelansicht/Artikel/europas-kunststofferzeuger-mit-freiwilliger-selbstverpflichtung.html
[Finkbeiner-2014]	Finkbeiner, M.; Ackermann, R.; Bach, V.; Berger, M.; Brankatschk, G.; Chang, Y.-J.; Grinberg, M.; Lehmann, A.; Martínez-Blanco, J.; Minkov, N.; Neugebauer, S.; Scheumann, R.; Schneider, L.; Wolf, K. (2014): Challenges in Life Cycle Assessment: An Overview of Current Gaps and Research Needs, 5, p. 207–258. Dordrecht: Springer (Background and Future Prospects in Life Cycle Assessment, 5)
[FNR-2017]	Fachagentur Nachwachsende Rohstoffe (2017): Informationen zu Biokunststoffen: Was sind Biokunststoffe? Last time checked: 2018, April 20. https://biowerkstoffe.fnr.de/fileadmin/biopolymere/dateien/pdfs/170703-Hintergrundinfo_BioKS.pdf
[Herdegen-2016]	Herdegen, J.; Benner, W.; Bokelmann K.; Hartfeil, T., Gellermann, C. (2016): Separationsmethoden zur Aufarbeitung von metallhaltigen Verbundwerkstoffen, p. 601–610. Neuruppin: TK Verlag (Recycling und Rohstoffe). Last time checked: 2018, April 20. http://www.vivis.de/phocadownload/Download/2016_rur/2016_RuR_601-610_Gellermann.pdf
[Hiebel-2017]	Hiebel, M.; Maga, D.; Kabasci, S.; Lieske, A.; Jesse, K.; Westphalen, C.; Bauer, J.; Kroll, L.; Rinberg, R.; Endres, H.-J.; Siebert-Raths, A.; Bellusová, D.; Mauer, S.; Kötter-Gribbe, S.; Mäurer, A.; Fell, T.; Dörgens, A. (2017): PLA-Abfälle im Abfallstrom. Last time checked: 2018, April 5.

https://news.fnr.de/fileadmin/allgemein/pdf/Pressemitteilungen/Ergebnisbericht-PLA-Abfaelle.pdf

[HVD-2017] Handelsverband Deutschland (2017): Vereinbarung zu Kunststofftragetaschen. Last time checked: 2018, April 20. https://www.einzelhandel.de/themeninhalte/umwelt-energie/372-umweltpolitik/themen/kunststofftragetaschen

[Marzi-2017] Marzi, T.; Deerberg, G.; Doetsch, C.; Grevé, A.; Hiebel, M.; Kaluza, S.; Maga, D.; Müller T.; Pflaum, H.; Pohlig, A.; Renner, M.; Seifert, U.; Stießel, S.; Unger, C.; Wack, T.; Weidner, E. (2017): Kohlendioxid, Biomasse und regenerativer Strom - Ressourcen einer neuen Kohlenstoffwirtschaft? Oberhausen: Karl Maria Laufen Verlag (UMSICHT-Diskurs Heft 1)

[Meyer-2017] Meyer, J.; Fey, D.; Krieg, S. (2017): Kunststoff-Sortierung aus Schredderrückständen mit Hochleistungs-Laserspektroskopie, 10, p. 193–198. Neuruppin: TK Verlag (Recycling und Rohstoffe, 10). Last time checked: 2018, April 20. http://www.vivis.de/phocadownload/Download/2017_rur/2017_RuR_193-198_Meyer.pdf

[Nonclercq-2016] Nonclercq, A. (2016): Mapping flexible pachaging in a Circular Economy [F.I.A.CE.]: Final Report. Last time checked: 2018, April 20. https://www.degruyter.com/view/j/pac.2012.84.issue-2/pac-rec-10-12-04/pac-rec-10-12-04.xml

[Oever-2017] van der Oever, M.; Molenveld, K.; van der Zee, M.; Bos, H. (2017): Biobased and biodegradable plastics - Facts and Figures: Focus on food packaging in the Netherlands (Rapport nr. 1722, p. 39ff). Last time checked: 2018, April 4. http://dx.doi.org/10.18174/408350

[PE-2018] Plastics Europe (2018): Plastics – the Facts 2017: An Analysis of European plastics production, demand and waste data. Last time checked: 2018, April 5. https://www.plasticseurope.org/application/files/5715/1717/4180/Plastics_the_facts_2017_FINAL_for_website_one_page.pdf

[PET-2016] GVM Gesellschaft für Verpackungsmarktforschung (2016): Aufkommen und Verwertung von PET-Getränkeflaschen in Deutschland 2015. Last time checked: 2018, April 9. http://www.forum-pet.de/rs/d/2016_09_22_Bericht_Verwertung%20PET-Getr%C3%A4nkeflaschen%202015.pdf

[Schwede-2018] Schwede, K.; Ißbrücker, C. (2018): Biokunststoffe im Recycling. In: *Müll und Abfall - Fachzeitschrift für Abfall und Ressourcenwirtschaft,* (4), p. 186–192

[Steinert-2016] Steinert Elektromagnetbau GmbH (2016): STEINERT präsentiert sortenreine Trennung schwarzer Kunststoffe auf der IFAT 2016: Steinert-Gruppe bringt neues optisches Sortiersystem UniSort BlackEye auf den Markt. Pressemitteilung. Last time checked: 2018, April 4. http://www.steinert-global.com/fileadmin/user_upload/germany/news/UniSort_Black-Eye_Press_Release_DE.pdf

[SYNVINA-2017]	SYNVINA (2017): Synvina receives interim approval from European PET Bottle Platform:: PEF to be integrated in circular economy. Pressemitteilung. Last time checked: 2018, April 4. https://www.basf.com/documents/corp/en/news-and-media/news-releases/2017/05/P229e_EPBP_recyclability_PEF.pdf
[TOMRA-oJ]	TOMRA (o. J.): Laser Objekt Detektierung: schwarze Kunststoffe, Glas. Last time checked: 2018, April 4. https://www.tomra.com/de-de/sorting/recycling/products/autosort/lod
[UMSICHT-2015]	Bertling, R.; Bertling, J.; Hiebel, M. (2015): Fraunhofer UMSICHT nimmt Stellung: Thema: Mikroplastik. Last time checked: 2018, April 9. https://www.umsicht.fraunhofer.de/content/dam/umsicht/de/dokumente/positionspapiere/2016/positionspapier-mikroplastik.pdf
[UMSICHT-2017]	Hiebel, M.; Nühlen, J.; Bertling, J. (2017): Zur Rolle der thermischen Abfallbehandlung in der Circular Economy. Oberhausen. Last time checked: DOI: 10.24406/UMSICHT-N-477482. http://publica.fraunhofer.de/eprints/urn_nbn_de_0011-n-4774822.pdf
[UN-2015]	United Nations (2015): Sustainable Development Goals - 17 Goals to transform our world. Last time checked: 2018, April 9. https://www.un.org/sustainabledevelopment/sustainable-development-goals/
[Unisensor-2014]	Unisensor (2014): Deutscher Umweltpreis. Pressemitteilung. Last time checked: 2018, April 4. http://www.unisensor.de/uploads/tx_mppress/Unisensor_Pressemitteilung_26.10.2014_13.pdf
[Unisensor-2016]	Unisensor (2016): Revolutionäres Kunststoffsortiersystem: schwarze Kunststoffe. Pressemitteilung. Last time checked: 2018, April 4. http://www.unisensor.de/uploads/tx_mppress/2016-09-29_Unisensor_Pressemitteilung_Powersort360_DE_06.pdf
[VerG-2017]	Bundesanzeiger Verlag (2017): Gesetz zur Fortentwicklung der haushaltsnahen Getrennterfassung von wertstoffhaltigen Abfällen. Last time checked: 2018, April 10. https://www.bgbl.de/xaver/bgbl/start.xav?start=//*%5b@attr_id=%27%27%5d#__bgbl__%2F%2F*%5B%40attr_id%3D%27bgbl117s2234.pdf%27%5D__1523338754014
[Vert-2012]	Vert, M.; Doi, Y.; Hellwich, K.-H.; Hess, M.; Hodge, P.; Kubisa, P.; Rinaudo, M.; Schué, F. (2012): Terminology for biorelated polymers and applications (IUPAC Recommendations 2012). In: *Pure and Applied Chemistry,* 84(2), p. 377–410
[Visionsort-2006]	Balthasar, D.; Rehrmann, V. (2006): VIS/NIR-Spektroskopie zur Wertstoffsortierung und Qualitätsanalyse. Last time checked: 2018, April 5. http://spectronet.de/story_docs/vortraege_2006/061005_farb_bv_ilmenau/061005_14_balthasar_titech.pdf
[Welt-2016]	Welt (2016): Ressourcenverbrauch: Ab sofort liegt die Erde im Minus. Last time checked: 2018, April 9. https://www.welt.de/wissenschaft/article157551951/Ab-sofort-liegt-die-Erde-im-Minus.html

[Zeit-2018] Zeit Online (2018): Plastikstrudel im Pazifik viermal größer als Deutschland. Last time checked: 2018, April 4. http://www.zeit.de/wissen/umwelt/2018-03/umweltverschmutzung-ozeane-muellstrudel-plastikmuell