EDP

Environmentally Degradable Polymeric Materials and Plastics

Guidelines to Standards and Testing Practices

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Preface

In the last decade, a large number of standard testing procedures and passing criteria for environmentally or bio-degradable plastics have been developed and established by various national and international organizations. Today there are more than 60 standards issued on EDP with a significant attention given to standard test methods for the assessment of various degradation processes and environments.

This handbook has been prepared in the hope of helping to increase awareness and understanding of the topics of standard testing procedures for EDP by providing introductory information on related aspects. It contains a complete list of standards issued by four major standardization organizations (i.e. ISO, ASTM, CEN, and DIN) including their classifications and analyses. A brief introduction to EDP and their different degradation processes is also presented. Targeted users of this handbook include laboratory staff, students, producers of EDP, and policy makers.

It must be noted that the process of development of new standards and the refinement of existing ones is ongoing. Users are highly recommended to follow up on the most current activities (e.g. revision, withdrawal, approval, or re-approval) of these standards.

What are EDP?

EDP are plastics designed to undergo a significant change in chemical structure under one or combined environmental conditions, resulting in a loss of some properties that may vary as measured by standard test methods appropriate to the plastics and the application in a period of time that determines its classification. [ASTM and ISO]

The development of EDP was initiated among several other attempts in the early 1980s to address an emerging global plastic waste problem, following decades of fast development and explosive growth of plastic utilization. Environmentally Degradable Plastics (EDP) are a new kind of plastic material, which is designed to exhibit a significant degradation resulting in environmentally compatible end products, namely, CO_2, water, and other substances (biomass) within an acceptable time frame.

Degradation of EDP is achieved by various mechanisms and their combination (photo, thermal, mechanical, hydrolytic, oxidative, and biological) with the ultimate degradation exclusively carried out by biological processes, known as “mineralization”. It is required that the degradation process of any EDP must be complete and without any accumulation of constituents with unknown environmental faith and risk.

EDP can be synthesized either from petrochemical or natural resources of vegetal, aquatic, and animal origins. The feedstocks are derived by three main routes: biosynthesis (e.g. fermentation by microorganisms), chemosynthesis (e.g. chemical synthesis and polymerization processes), and a direct application of natural materials with or without chemical modification (e.g. fibers or extracts). Groups of starting compounds currently utilized or being developed for the production of EDP are shown in Table1.

The future of EDP is promising both in the markets for niche products (medical and pharmaceutical applications), as well as high volume products such as single use disposable hygiene products, agricultural films, and most importantly packaging materials.
To their high volume and short service life of the last categories, the use of EDP promises a significant alleviation of environmental burdens imposed by traditional plastics.

So far only limited success of EDP has been realized. Most currently commercialized products are focused on agricultural mulch films, foam-liked food containers, and shopping bags. A much wider spectrum of uses is being actively investigated. Major barriers to their diffusion are (i) high production cost due to small production volume and expensive R&D investments, (ii) lack of market and policy incentives for environmentally sound materials, and (iii) limited public awareness and acceptance.

Table 1. List of classes of polymers used for the production of EDP.

Feedstocks for EDP	
Biological Origin	**Synthetic Origin**
Proteins	Aliphatic polyesters
Albumin	Poly(glycolic acid), PGA
Casein	Poly(lactic acid), PLA
Collagen/gelatin	Poly(lactide-co-glycolide), PLAGA
Fibrinogen/fibrin	Poly(β-hydroxy alkanoate), PHA
Wheat gluten, soy protein	Poly(β-hydroxy butyrate), PHB
Zein	Poly(β-hydroxy butyrate-co-valerate), PHBV
	Poly(β-malic acid), PMLA
Polysaccharides	Poly(ε-caprolactone), PCL
Animal	Poly(alkylene succinate)s
Heparin	Poly(p-dioxanone), PDO
Hyaluronic acid	Poly(ethylene terephthalate) modified
Chitin/Chitosan	Copolyesters
Vegetal	Ecoflex, EastarBio, Biomax
Cellulose and derivatives	Poly(vinyl alcohol)
Lignin	Polyamides
Starch and derivatives	Copolyamides
Microbial Fermentation	Poly(ester amides)
Dextran	Poly(amino acids)
Xanthan	Pseudopoly(α-amino acids)
Pullulan	Poly(α-amino acid ester)
Plant algae/extracts	Poly(ester-ureas)
Pectin	Poly(iminocarbonates)
Inulin	Polyanhydrides
Alginate	Poly(ethyleneglycol)/Poly(orthoester)s
Carrageenan	Polyphosphazenes
Agar	Polyurethanes, PUR
Gums	Poly(ester urethane), AU
Xyloglucan	Poly(ether urethane), EU
Levan	Poly(urethane urea)s, PUU
	Polyolefins

Degradation Process

ASTM and ISO define Degradation as “an irreversible process leading to a significant change of the structure of a material, typically characterized by a loss of properties (e.g. integrity, molecular weight, structure or mechanical strength) and/or fragmentation. Degradation is affected by environmental conditions and proceeds over a period of time comprising one or more steps”.

When plastics are exposed to an energetic environment of corresponding energy values of the material it results in the breaking of the polymeric bonds, the beginning of their degradation. In the environment this process relies on a combination of various mechanisms, and eventually combinations thereof, notably, thermal (heat), photo (sunlight), oxidative (oxygen), hydrolytic (water), mechanical (stress), and bio (microorganisms).

The process can be viewed as comprising two phases, disintegration and mineralization, see Fig.1. The initial phase of the disintegration process is significantly associated with the deterioration in physical properties, such as discoloration, embrittlement, and fragmentation. The second phase is the ultimate conversion of plastic fragments, after being broken down to molecular sizes, to CO_2, water, biomass, and CH_4 in the case of anaerobic conditions.

All plastics degrade; however, the important question for distinguishing non-degradable plastics from EDP is for over what period of time the degradation process takes place. The key to the design of EDP is the acceleration of the degradation process especially in the initial phase. Each type of EDP is usually more susceptible to attack through mainly one of many available mechanisms. The maximum degradation of EDP can only by realized by exposing them in a proper environment, mostly resembling the conditions for which the materials are designed.

The time determining step in the degradation process of traditional plastics as well as EDP is the initial phase, also known as the lag phase. For EDP, the degradation rate is greatly enhanced by addition of easily degradable components such as starch or hydrolysable groups (e.g. polyesters, polyanhydrides, or polyamides). Another approach is the addition of active components, such as the use of photo-sensitive additives in

EDP. Upon exposure to the sun's UV rays, these additives release free radicals which will randomly attack and break the polymeric bonds leading to the formation of lower molecular weight products.

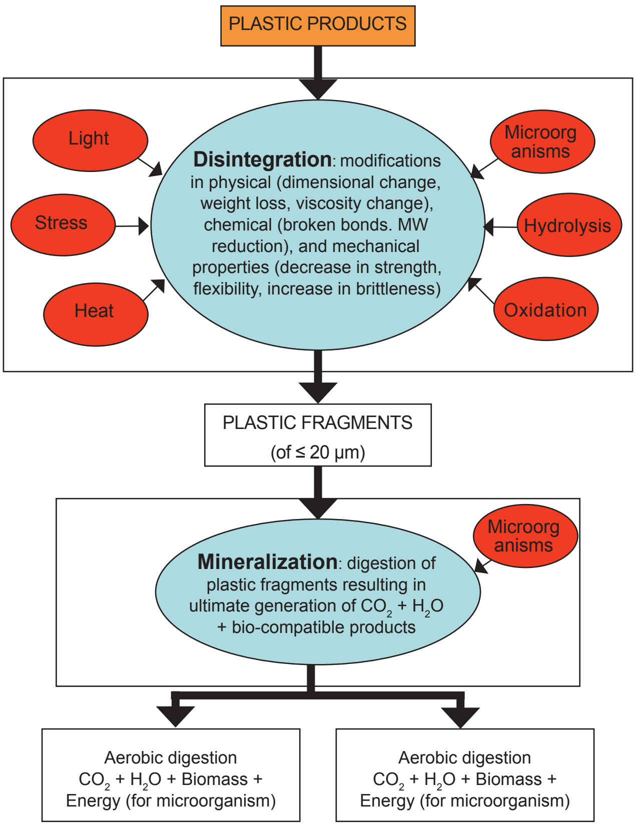

Figure 1. Degradation process of EDP can be considered as comprising of two major phases, disintegration and mineralization.

The plastics that degrade in the first stage through hydrolytic processes can then by classified as “hydrobiodegradable”, whereas plastics degrading via a preliminary thermally or photophysically induced oxidation enter the class of “oxobiodegradable”.

Mechanisms of plastics degradation

Photo degradation

It is typically induced by addition of photo-sensitive additives. These additives, when exposed to the sun’s UV rays, release free radicals which randomly attack and break the polymeric bonds that are susceptible to be oxidized under aerobic conditions.

Mechanical degradation

This process involves the application of force to break apart the plastics. It is a notable method for size reduction.

Thermal degradation

The asserted heat provides the required energy for promoting the oxidation of the carbon in the polymer backbone of molecules constituting the plastics.

Oxidative degradation

This process is coupling with previous thermal and photophysical degradation and involves the reaction of oxygen with the polymer.

Hydrolytic degradation

This process requires the presence of hydrolysable groups such as ester or amide groups present in starch, polyesters, polyanhydrides, polycarbonates, polyamides, or polyurethanes. These compounds absorb moisture from the environment lending hydrolytic cleavage of polymer chains driven by chemical agents or mediated by enzymes.

Bio degradation

The breaking of polymeric bonds is associated with the action of enzymes, the living organisms, and/or their secretion products. The process is greatly affected by the amounts and types of available microorganisms and their microbial activities, which are sensitive to temperature, moisture, pH, C/N ratio, and the amount of available oxygen. The process can occur outside of the cells (exobiodegradation) or within the cells (endo-biodgradation) or eventually through a combination of the two mechanisms.

Standards and Certifications

The establishment of standards in the field of EDP is relatively new. The first standard testing practice for biodegradability and compostability of plastic products was issued by the American Society for Testing and Materials (ASTM) in 1999, although prior to that (1992 - 1997) several standard practices for testing of biodegradation of organic compounds in aqueous media had already been issued by the International Organization for Standardization (ISO). A number of institutions both in the national and international levels are increasingly involved in the process of development and/or adoption of these standards on EDP, see Table 2.

Table 2. Organizations leading the development of standards on EDP.

Organization and Technical Committee	Country	Number of Standards	Nature of Adoption
American Society for Testing and Materials ASTM D20.96 (http://www.iso.org)	USA	26	Voluntary
International Organization for Standardization ISO TC61/SC5 ISO TC61/SC6 (http://www.astm.org)	International	23 5	Voluntary
European Committee for Standardization CEN TC261 (http://www.cenorm.be)	European Union	8	Legislative*

*** Must be converted to National Norm by EU countries.**

The internationally recognized standardization body is represented by ISO whereas ASTM and CEN can be considered as regional standardization bodies. In addition, there are also a number of national standardization bodies, such as the Austrian Standard Institute (ÖNORM), the British Standards Institute (BSI), and the Biodegradable Plastics Society (BPS) of Japan.

In general, a standard is a published document which sets out specifications or procedures, designed to ensure that a material, product, method or service is fit for its purpose and consistently performs the way it is proposed to. It is also required to have a general specific validity. The development of standards on EDP serves as a critical element not only in the process of quality assurance but also in shaping of further advances and commercialization of EDP products.

Standards on EDP represent means for a product or a group of products to be verified and confirmed on the same scientifically sound basis, which brings consistency, accountability, and reliability to the results and thus to the products. They constitute a ground for establishing an overall testing scheme including basic requirements and distinct pass levels for subsequent certification and labels. Labeling of qualified products is an important communication and promotional tool, e.g. from producers to other involved parties such as the consumers or municipal staff. Table 3 lists some of currently available labels, their certifying bodies, and the required Standards.

It is very important to distinguish between “compostable” and “biodegradable” products (refer to the Glossary of common terminologies in EDP in this handbook). A product that is “compostable” must be biodegradable. However, the reverse logic is not necessarily true. In other words, if a product can be shown to be “biodegradable” in composting environments (i.e. municipal composting facilities or household compost piles), then it can be claimed as “compostable”. Biodegradable materials which degrade in periods longer than the typical composting cycle (4 to 6 months), they would be termed biodegradable but not compostable. Compostable products are also subjected to additional rules and regulations applied on composts from regular sources.

Given the importance of composting which is considered to be the most ecological waste treatment method, it is not surprising that the majority of more than 60 published standards on EDP is related to aerobic degradation tests in composting conditions. More over, four out of six labels shown in Table 3 are for “compostable” products.

Table 3. Certification schemes and labels for EDP products.

Country	Organization	Standards Compliance	Symbol
USA	Biodegradable Products Institute	ASTM D6400	BPI Biodegradable Products Institute promoting biodegradable products throughout the world
Germany	International Biodegradable Polymers Association and Working Groups	DIN V 54900 or EN 13432 or ASTM D6400	kompostierbar
Japan	Biodegradable Plastics Society	ISO 14851ff. and OECD 301C and JIS K 6950 ff.	グリーンプラ 生分解性プラスチック
Finland	Jätelaito Syhdistys	EN 13432 and ISO 14851 ff.	
Belgium	AIB Vinçotte	EN 13432 and ISO 14851 ff.	OK bio-degradable OK compost

Standards Inventory

The following organizations are the key players contributing to the development and issuing of standards on EDP.

American Society for Testing and Materials International (ASTM)
http://www.astm.org
The committee responsible is the D20.96 (committee D20 working on plastics and subcommittee 96 on environmentally degradable plastics and biobased products). There are currently 26 active standards and 10 work items under development, see Tables 4 and 5 Note that a number of published standards that were later withdrawn (e.g. D5152, D5437, D5509, D5512, and D5525) are not included in the Table 4.

International Organization for Standardization (ISO)
www.iso.org
Most standards are issued under the committee T61/SC5/WG22 (technical committee TC61 working on plastics, subcommittee SC5 on physical and chemical properties, and working group WG22 on biodegradable plastics). There are currently 23 active standards and 4 work items under development, see Tables 6 and 7.

European Committee for Standardization (CEN)
http://www.cenorm.be/cenorm/index.htm
The committee responsible is the TC261/SC4/WG2 (technical committee TC261 working on packaging, subcommittee SC4 on environmental matters, and working group WG2 on degradability and compostability). The adoption of CEN standards and norms are required for all EU member countries. There are currently 8 active standards and 8 items under development, see Tables 8 and 9. Many of the CEN standards are based on ISO standards.

German Institute for Standardization (DIN)
http://www2.din.de
The committee responsible is the DIN FNK 103.3. There are currently 9 active standards, see Table 10, four of which are originally developed by DIN, i.e. the DIN V 54900 ff.

Table 4. List of 26 standards published by ASTM D20.96 committee.

ASTM Active Standards	Description
D3826 - 98 (2002)	Standard Practice for Determining Degradation End Point in Degradable Polyethylene and Polypropylene Using a Tensile Test.
D5071 - 99 *	Standard Practice for Exposure of Photodegradable Plastics in a Xenon Arc Apparatus.
D5208 - 01	Standard Practice for Fluorescent Ultraviolet (UV) Exposure of Photodegradable Plastics.
D5209 - 92	Standard Test Method for determining the Aerobic Biodegradation of Plastic Materials in the Presence of Municipal Sewage Sludge.
D5210 - 92 (2002)	Standard Test Method for Determining the Anaerobic Biodegradation of Plastic Materials in the Presence of Municipal Sewage Sludge.
D5247 - 92	Standard Test Method for Determining the Anaerobic Biodegradability of Degradable Plastics by Specific Microorganisms.
D5271 - 02	Standard Test Method for Determining the Anaerobic Biodegradation of Plastic Materials in an Activated-Sludge-Wastewater-Treatment System.
D5272 - 92 (1999)	Standard Practice for Outdoor Exposure Testing of Photodegradable Plastics.
D5338 - 98 (2003)	Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials Under Controlled Composting Conditions.
D5510 - 94 (2001) *	Standard Practice for Heat Aging of Oxidatively Degradable Plastics.
D5511 - 02	Standard Test Method for Determining Anaerobic Biodegradation of Plastic Materials Under High-Solids Anaerobic-Digestion Conditions.
D5526 - 94 (2002)	Standard Test Method for Determining Anaerobic Biodegradation of Plastic Materials Under Accelerated Landfill Conditions.
D5951 - 96 (2002)	Standard Practice for Preparing Residual Solids Obtained After Biodegradability Standard Methods for Plastics in Solid Waste for Toxicity and Compost Quality Testing.
D5988 - 03 *	Standard Test Method for Determining Aerobic Biodegradation in soil of Plastic Materials or Residual Plastic Materials After Composting.

D6002 - 96 (2002)e1	Standard Guide for Assessing the Compostability of Environmentally Degradable Plastics.
D6003 - 96	Standard Test Method for Determining Weight Loss From Plastic Materials Exposed to Simulated Municipal Solid-Waste (MSW) Aerobic Compost Environment.
D6340 - 98	Standard Test Methods for Determining Aerobic Biodegradation of Radiolabeled Plastic Materials in an Aqueous or Compost Environment.
D6400 - 99e1 *	Standard Specification for Compostable Plastics.
D6691 - 01	Standard Test Method for Determining Aerobic Biodegradation of Plastic Materials in the Marine Environment by a Defined Microbial Consortium.
D6692 - 01	Standard Test Method for Determining the Biodegradability of Radiolabeled Polymeric Plastic Materials in Seawater.
D6776 - 02	Standard Test Method for Determining Anaerobic Biodegradability of Radiolabeled Plastic Materials in a Laboratory-Scale Simulated Landfill Environment.
D6852 - 02	Standard Guide for Determination of Biobased Content, Resources Consumption, and Environmental Profile of Materials and Products.
D6866 - 04a *	Standard Test Methods for Determining the Biobased Content of Natural Range Materials Using Radiocarbon and Isotope Ratio Mass Spectrometry Analysis.
D6868 - 03	Standard Specification for Biodegradable Plastics Used as Coatings on Paper and Other Compostable Substrates.
D6954 - 04	Standard Guide for Exposing and Testing Plastics that Degrade in the Environment by a Combination of Oxidation and Biodegradation.
D7026 - 04	Standard Guide for Sampling and Reporting of Results for Determination of Biobased Content of Materials via Carbon Isotope Analysis.

D **Designation number - year of original adoption or last revision (year of reapproval) e number of editorial change**

***** **indicating a revision is being proposed to the current standard, see Table 5.**

Table 5. List of 10 work items currently under development by ASTM D20.96 committee.

ASTM Current Work Items	Details
WK2406	Proposed revision to existing D5510 - 94 (2001) standard.
WK2756	Proposed revision to existing D5988 - 03 standard.
WK2980	Standard Guide for Sampling and Reporting of Results for Determination of Biobased Content of Materials via Carbon Isotope Analysis.
WK3058	Propose new standard on "Standard Practice for Evaluating and Reporting Environmental Performance of Biobased Products".
WK3184	Proposed revision to existing D5071 - 99 standard.
WK4649	Propose new standard on "Standard Specification for Biodegradable Plastics in the Marine Environment".
WK4693	Proposed revision to existing D6400 - 99 e1 standard.
WK4822	Proposed revision to existing D6866 - 04a standard.
WK4857	Propose new standard on "Standard Specification for Single-Use Biodegradable and Biobased Biodegradable Plastic Utensils".
WK5489	Proposed revision to existing D6866 - 04a standard.

WK = Work Item
(WK refers to a technical document in the development stage, which will become either a new standard or a revision to an existing standard.)

Table 6. List of 23 standards published by ISO TC61/SC5 committee.

ISO Standards	Description
ISO 7827:1994	Water quality - Evaluation in an aqueous medium of the "ultimate" aerobic biodegradability of organic compounds - Method by analysis of dissolved organic carbon (DOC).
ISO 9408:1999	Water quality - Evaluation of ultimate aerobic biodegradability of organic compounds in aqueous medium by determination of oxygen demand in a closed respirometer.
ISO 9439:1999	Water quality - Evaluation of ultimate aerobic biodegradability of organic compounds in aqueous medium - Carbon dioxide evolution test.
ISO 9887:1992	Water quality - Evaluation of the aerobic biodegradability of organic compounds in an aqueous medium - Semi-continuous activated sludge method (SCAS).
ISO 9888:1999	Water quality - Evaluation of ultimate aerobic biodegradability of organic compounds in aqueous medium - Static test (Zahn-Wellens method).
ISO 10634:1995	Water quality - Guidance for the preparation and treatment of poorly water-soluble organic compounds for the subsequent evaluation of their biodegradability in an aqueous medium.
ISO 10707:1994	Water quality - Evaluation in an aqueous medium of the "ultimate" aerobic biodegradability of organic compounds - Method by analysis of biochemical oxygen demand (closed bottle test).
ISO 10708:1997	Water quality - Evaluation in an aqueous medium of the ultimate aerobic biodegradability of organic compounds - Determination of biochemical oxygen demand in a two-phase closed bottle test.
ISO 11266:1994	Soil quality - Guidance on laboratory testing for biodegradation of organic chemicals in soil under aerobic conditions.
ISO 11733:2004	Water quality - Determination of the elimination and biodegradability of organic compounds in an aqueous medium - Activated sludge simulation test.
ISO 11734:1995	Water quality - Evaluation of the "ultimate" anaerobic biodegradability of organic compounds in digested sludge - Method by measurement of the biogas production.

ISO 14592-1:2002	Water quality - Evaluation of the aerobic biodegradability of organic compounds at low concentrations - Part 1: Shake-flask batch test with surface water or surface water/sediment suspensions.
ISO 14592-2:2002	Water quality - Evaluation of the aerobic biodegradability of organic compounds at low concentrations - Part 2: Continuous flow river model with attached biomass.
ISO 14593:1999	Water quality - Evaluation of ultimate aerobic biodegradability of organic compounds in aqueous medium - Method by analysis of inorganic carbon in sealed vessels (CO_2 headspace test).
ISO 14851:1999	Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium - Method by measuring the oxygen demand in a closed respirometer.
ISO 14852:1999	Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium - Method by analysis of evolved carbon dioxide.
ISO 14855:1999 *	Determination of the ultimate aerobic biodegradability and disintegration of plastic materials under controlled composting conditions - Method by analysis of evolved carbon dioxide.
ISO/TR 15462:1997	Water quality - Selection of tests for biodegradability.
ISO 15473:2002	Soil quality - Guidance on laboratory testing for biodegradation of organic chemicals in soil under anaerobic conditions.
ISO 16221:2001	Water quality - Guidance for determination of biodegradability in the marine environment.
ISO 16929:2002	Plastics - Determination of the degree of disintegration of plastic materials under defined composting conditions in a pilot-scale test.
ISO 17556:2003	Plastics - Determination of the ultimate aerobic biodegradability in soil by measuring the oxygen demand in a respirometer or the amount of carbon dioxide evolved.
ISO 20200:2004	Plastics - Determination of the degree of disintegration of plastic materials under simulated composting conditions in a laboratory-scale test.

ISO Designation number: year of original adoption or last revision
TR = Technical Report
*** indicating a revision is being proposed to the Standard, see Table 7.**

Table 7. List of 4 work items currently under development by ISO TC61/SC5 committee.

ISO Current Work Items	Details
ISO/PRF 14853	Plastics - Determination of the ultimate anaerobic biodegradation of plastic materials in an aqueous system - Method by measurement of biogas production.
ISO 14855:1999/Amd 1	Determination of the ultimate aerobic biodegradability and disintegration of plastic materials under controlled composting conditions - Method by analysis of evolved carbon dioxide; Amendment 1: Use of activated vermiculite instead of mature compost.
ISO/AWI 14855-2	Determination of the ultimate aerobic biodegradability and disintegration of plastic materials under controlled composting conditions - Part 2: Gravimetric measurement of carbon dioxide evolved in a laboratory-scale test.
ISO/PRF 15985	Plastics - Determination of the ultimate anaerobic biodegradation and disintegration under high-solids anaerobic-digestion conditions - Method by analysis of released biogas.

Amd = Amendment
AWI = Approved work item
PRF = Proof of a new international standard
(Amd is a document which provides supplementary information to an existing standard. It is normally issued as an advance notice of changes or additions before the complete revision can be issued.)

Table 8. List of 8 standards CEN TC261 committee related to testing of EDP.

CEN Standards	Description
EN 13432:2000 *	Packaging - Requirements for packaging recoverable through composting and biodegradation - Test scheme and evaluation criteria for the final acceptance of packaging.
EN 14045:2003	Packaging - Evaluation of the disintegration of packaging materials in practical oriented tests under defined composting conditions.
EN 14046:2003	Packaging - Evaluation of the ultimate aerobic biodegradability of packaging materials under controlled composting conditions - Method by analysis of released carbon dioxide.
EN 14047:2002	Packaging - Determination of the ultimate aerobic biodegradability of packaging materials in an aqueous medium - Method by analysis of evolved carbon dioxide.
EN 14048:2002	Packaging - Determination of the ultimate aerobic biodegradability of packaging materials in an aqueous medium - Method by measuring the oxygen demand in a closed respirometer.
EN ISO 14851:2004	Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium - Method by measuring the oxygen demand in a closed respirometer (ISO 14851:1999).
EN ISO 14852:2004	Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium - Method by analysis of evolved carbon dioxide (ISO 14852:1999).
EN ISO 14855:2004	Determination of the ultimate aerobic biodegradability and disintegration of plastic materials under controlled composting conditions - Method by analysis of evolved carbon dioxide (ISO 14855:1999).

EN Designation number: year of original adoption or last revision
*** indicating a revision is being proposed to the Standard, see also Table 9.**

Table 9. List of 8 draft standards under development by CEN TC261 committee related to testing of EDP.

CEN Standards (under development)	Details
N/A	Plastics - Degradable plastics - Guidance, definitions and terminology.
N/A	Plastics - Evaluation of degradability in soil - Test scheme for final acceptance and specifications.
EN 13432:2000/prAC	Packaging - Requirements for packaging recoverable through composting and biodegradation - Test scheme and evaluation criteria for the final acceptance of packaging.
prEN 14806	Packaging - Preliminary evaluation of the disintegration of packaging materials under simulated composting conditions in a laboratory scale test.
prEN 14987	Plastics - Evaluation of disposability in waste water treatment plants - Test scheme for final acceptance and specifications.
prEN 14995	Plastics - Evaluation of Compostability - Test Scheme and Specifications.
prEN ISO 17556	Plastics - Determination of the ultimate aerobic biodegradability in soil by measuring the oxygen demand in a respirometer or the amount of carbon dioxide evolved (ISO 17556:2003).
prEN ISO 20200	Plastics - Determination of the percentage disintegration in a laboratory composting environment.

N/A = Not available
prAC = Draft Amendment
prEN = Draft Standard

Table 10. List of 9 standards DIN FNK 103.3 committee.

DIN Standards	Description
DIN V 54900-1	Testing of compostability of plastics - Part 1: Chemical testing
DIN V 54900-2	Testing of compostability of plastics - Part 2: Testing of the complete biodegradability of plastics in laboratory tests
DIN V 54900-3	Testing of compostability of plastics - Part 3: Testing under practice - relevant conditions and a method of testing the quality of the composts
DIN 54900-4	Testing of the compostability of polymeric materials - Part 4: Testing of the eco-toxicity of the composts.
DIN EN 13432	Requirements for packaging recoverable through composting and biodegradation - Test scheme and evaluation criteria for the final acceptance of packaging.
DIN EN 14045	Evaluation of the disintegration of packaging materials in practical oriented tests under defined composting conditions.
DIN EN 14995	Plastics - Evaluation of compostability - Test scheme and specifications.
DIN EN ISO 14851	Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium - Method by measuring the oxygen demand in a closed respirometer (ISO 14851:1999).
DIN EN ISO 14852	Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium - Method by analysis of evolved carbon dioxide (ISO 14852:1999).

DIN Designation number

Analyse of Standards

This section presents some additional comments on standards related to biodegradability test procedures. The fact that they account for the greater part of the standards: 42 of 66 standards issued so far by ASTM, ISO, CEN, and DIN, demonstrates the recognition by these organizations of the significance of biodegradation as the only mechanism enabling ultimate degradation. These standards are varied in system requirements, complexity, and capability. However, in all cases the determination of the degradation process is assessed by measuring one of three parameters: carbon dioxide (CO_2) evolution, consumption of biochemical and chemical oxygen demand (BOD and COD), or reduction of the Dissolved Organic Carbon (DOC).

There are three types of biodegradability, "**Ready**" biodegradability, "**Inherent**" (or "Potential") biodegradability, and "**Ultimate**" biodegradability. Each standard procedure employs a specific analytical technique and testing conditions, which are suitable for the determination of a certain type of biodegradability. Therefore, the understanding of their differences is crucial for both the selection of appropriate standard for testing and consequential interpretation of the results.

The distinction between these different types of biodegradability may be best explained by the following example (see also the Glossary of common terminologies): a cellulose paper, which is used as a positive reference in the biodegradability test, demonstrates 60% "Ready" biodegradability, 90% "Inherent" biodegradability, and 30% "Ultimate" biodegradability in landfill conditions.

To assist in the selection and organization of the examination, standards for biodegradability testing can be further classified into 3 levels (see Table 11): **preliminary**, **simulated**, and **complimentary** tests. The preliminary tests typically correspond to the determination of the "Ready" biodegradability and should be carried out in as an initial screening step. They are less stringent in nature and are often carried out in a simplified environment such as in aqueous or in soil. Positive results from these preliminary tests are a good indicator that the material under investigation can readily degrade in most natural environments.

A more comprehensive examination of the degradation process, e.g. the determination of degradation rates or the concentration of by products, is possible in simulated or accelerated procedures. These tests are usually carried out at lower concentrations in a targeted environment, demanding special measurement techniques and particular preparation procedures. Hence many of them are used to constitute the ground for certifications of EDP products, see Table 3. These tests are carried out mainly with the intention of examining the degradation behavior in specific environmental conditions (e.g. composting, landfills, and marine condition), therefore their results are indicative of the “Ultimate” biodegradability of the material in the selected environment.

Complementary tests are generally conducted to provide alternative or supplementary data on the materials. Examples are tests carried out to examine degradation behavior in anaerobic conditions and tests for determination of the “Inherent” biodegradability. In the case of “Inherent” biodegradability, a favorable test conditions are often tailored for these investigations to yield the degradation results of the highest potential. Therefore, such results from this type of preliminary tests must be deemed with cautious especially when an estimation of the real world conditions is to be derived.

Table 12 shows characteristics of standards on degradation test methods by ASTM and ISO. These standards are identified according to the degradation mechanisms (i.e. bio, photo, thermal, and oxidative) and the designed test environments (i.e. composting, municipal sewage sludge, aqueous, landfill, and others). In some cases where there exists an equivalent standard, it is presented in the brackets. The majority of these standards address the biodegradability tests in aqueous and composting environments. With composting increasing in Europe and the significance of biodegradation as the only mechanism enabling the ultimate degradation, the emphasis is sensible.

Table 11. Classification of level of tests for biodegradability.

Level of Tests	Measured Parameters	Test Characteristics	Related ASTM and ISO Standards
Preliminary **Ready biodegradability**	DOC[1] BOD[2] CO_2 Inorganic Carbon	- Screening test - High substance loading (2-100 mg/l) - Indicative of rapid degradability in general environment conditions	D5209 ISO7827, ISO9408, ISO9439, ISO10707, ISO10708,ISO14593, ISO14851,ISO14852, ISO16221, ISO17556
Simulation **Ultimate biodegradability**	DOC BOD CO_2 ^{14}C-radiolebelling	- Ultimate biodegradability test with focus on the determination of degradation rate - Specific environment conditions - Low substance loading (≤100 µg/l) (High substance loading can be performed if identification and quantification of major byproducts are to be done.)	D5338, D5988, D6002, D6340, D6400, D6776, D6691, D6954 ISO11733, ISO14592 ff., ISO14855
Complimentary **Inherent biodegradability**	CO_2 Inorganic Carbon	- Ultimate biodegradability test - Prolonged exposure - Indicative of intrinsic biodegradability	ISO9887, ISO9888
Anaerobic biodegradability screening	CO_2 CH_4 Inorganic Carbon	- Screening test - Anoxic environment conditions - High substance loading - Indicative of anaerobic biodegradability (i.e. sludge digester or compost vessel)	D5210, D5247, D5271, D5511, D5526, D6776 ISO11734

DOC = Dissolved Oxygen Carbon

BOD = Biochemical Oxygen Demand

Table 12. Analyse of standards according to test environment and degradation mechanisms.

Standards	Mechanism of Degradation					Testing Environment					Comments [Equivalent Standards]
	Biodegradation		Photo	Thermal	Oxidation	Composting	MS Sludge	Aqueous	Landfill	Others	
	Aerobic	Anaerobic									
D3826 - 98 (2002)											degradation end point by tensile test
D5071 - 99			√							√	Xenon arc apparatus
D5208 - 01			√							√	Ultraviolet exposure
D5209 - 92	√						√				
D5210 - 92 (2002)		√					√				[ISO 11734:1995]
D5247 - 92		√								√	in culture Medium
D5271 - 02		√					√				activated sludge
D5272 - 92 (1999)										√	outdoor exposure
D5338 - 98 (2003)	√					√					controlled conditions [ISO 14855:1999]
D5510 - 94 (2001)				√						√	in incubators
D5511 - 02		√								√	high solid loading
D5526 - 94 (2002)		√							√		accelerated conditions
D5988 - 03	√									√	in soil
D6340 - 98	√					√		√			for radio labeled plastic materials
D6691 - 01	√									√	in marine environment [ISO 16221:2001]
D6692 - 01										√	in sea water for radio labeled plastic materials
D6776 - 02		√							√		for laboratory scale
D6954 - 04	√	√			√	√			√	√	also in soil

ISO 7827:1994	√							√			DOC method for organic compounds
ISO 9408:1999	√							√			O_2 demand for organic compounds
ISO 9439:1999	√							√			evolved CO_2 for organic compounds
ISO 9887:1992	√							√			SCAS method for organic compounds
ISO 9888:1999	√						√				Zahn-Wellens test for organic compounds
ISO 10707:1994	√							√			biochemical O_2 demand for organic compounds
ISO 10708:1997	√							√			biochemical O_2 demand in two-phase closed bottle test for organic compounds
ISO 11733:2004	√							√			activated sludge for organic compounds
ISO 11734:1995		√					√				for organic compounds [D5210 - 92 (2002)]
ISO 14592-1:2002	√									√	Shake-flask test for organic compounds
ISO 14592-2:2002	√									√	simulated river condition for organic compounds
ISO 14593:1999	√							√			CO_2 headspace test for organic compounds
ISO 14851:1999	√							√			O_2 demand for plastics
ISO 14852:1999	√							√			evolved CO_2 for plastics
ISO 14855:1999	√					√					evolved CO_2 for plastics [D5338 - 98 (2003)]
ISO 16221:2001	√									√	in marine environment [D6691 - 01]
ISO 16929:2002						√					pilot scale disintegration test for plastics
ISO 17556:2003	√									√	in soil for plastics
ISO 20200:2004						√					lab scale disintegration test for plastics

DOC = dissolved organic carbon

SCAS = semi-continuous activated sludge

Glossary

Terminology	Definition
Aerobic degradation	Degradation in the presence of air. Composting is a way of aerobic degradation. [DEH]
Anaerobic degradation	Degradation in the absence of air, as occurs in dry landfills. Anaerobic degradation is also called biomethanisation. [DEH]
Assimilation	The conversion of nutriments into living tissue; constructive metabolism. [DEH]
Biodegradability **"Ready" Biodegradability** **"Inherent" Biodegradability** **"Ultimate" Biodegradability**	The ability of a substance to be broken down into simpler substances by living things especially by microorganisms. [1] The biodegradability of a substance achievable in a short period of time after being exposed to the most common environment. Examples of tests for the determination of this type of biodegradability include Close - Bottle test and Die - Away test. A positive result from these tests implies that the substance can readily degrade in the natural environment. The biodegradability of a substance achievable in the most favorable (for degradation) environment. Examples of tests for the determination of this type of biodegradability include Zahn - Wellens test and Semi - Continuous Activated Sludge (SCAS) method. A positive result from these tests implies that the substance can degrade and will not persist in the environment, although the degradation process will be a slow one. The biodegradability of a substance achievable in a chosen environment, particularly designed to simulate a situation of interest (e.g. composting, landfill, marine, and etc.). The most common test method is CO_2 evolution. A positive test result implies that the substance can degrade in the environment similar to the testing conditions.
Biodegradable	Capable of undergoing decomposition into carbon dioxide, methane, water, inorganic compounds, or biomass in which the predominant mechanism is the enzymatic action of microorganisms, that can be measured by standardised tests, in a specified period of time, reflecting available disposal condition. [ASTM] Potential of a material to be degraded caused by biological activity especially by enzymatic action leading to a significant change of the chemical structure of the material. [CEN] Capable of being broken down chemically by the action of microorganisms. [ISWA]
Biodegradable plastic	A degradable plastic in which the degradation results from the action of naturally occurring microorganisms such as bacteria, fungi and algae. [ASTM]
Biodegradation	Degradation process, which is caused by biological activity, especially by the enzymatic action of microorganisms. [DEH]
Biomass	The weight of all the organisms in a given population. [DEH]

Carbon Dioxide (CO_2) Evolution test	A test method for determining "Ready" biodegradability. The test is performed in a closed system with a constant supply of carbon free air. Degradation is determined by the amount of CO_2 produced dissolved in a scrubbing liquid.
Closed - Bottle test	A test method for determining "Ready" biodegradability. The test is performed in a closed system with no air flow and relatively small amount of microorganisms. The degree of degradation is determined by the decrease of O_2 content of the medium, i.e. used up by microbial activities, which is a function of the Biochemical Oxygen Demand (BOD) and Theoretical Oxygen Demand (ThOD) or Chemical Oxygen Demand (COD).
Compostable	Degradation by biological processes during composting to yield carbon dioxide, water, inorganic compounds and biomass at a rate consistent with other known compostable materials and leave no visually distinguishable or toxic residues. [ASTM and ISO] Property of a packaging to be biodegraded in a composting process. [CEN] Capable of undergoing biological decomposition in a compost site, to the extent that they are not visually distinguishable and break down to carbon dioxide, water, inorganic compounds, and biomass, at a rate consistent with known compostable materials (e.g. cellulose). [DEH]
Compostable plastic	A plastic that undergoes degradation by biological processes during composting to yield CO_2, water, inorganic compounds and biomass at a rate consistent with other compostable materials and leaves no visible, distinguishable or toxic residue. [ASTM] A polymer is "compostable" when it is biodegradable under composting conditions. The polymer must meet the following criteria:a) Break down under the action of microorganisms (bacteria, fungi, and algae); b) Total mineralisation is obtained (conversion into CO_2, H_2O, inorganic compounds andbiomass under aerobic conditions); c) The mineralisation rate compatible with the composting process and consistent with known compostable materials (e.g. cellulose). [DEH]
Composting	The activity of breaking down plant and animal material using microorganisms under aerobic conditions. For successful composting there must be sufficient water and air to allow the microorganisms to break down the material, and the compost should reach and maintain a warm temperature. [DEH]
Concawe test	A test method originally developed by the European Oil Companies' Organization for Environment, Health, and Safety (CONCAWE) for determining the "Inherent" biodegradability of oil products. It is equivalent to Head - Space test.
Degradability	Ability of materials to break down, by bacterial (biodegradable), thermal (oxidative) or ultraviolet (photodegradable) action. [DEH]
Degradable	A material is called degradable with respect to specific environmental conditions if it undergoes degradation to a specific extent within a given time measured by specific standard test methods. [ASTM, ISO, and CEN] Degradable materials break down, by bacterial (biodegradable), thermal (oxidative) or ultraviolet (photodegradable) action. [DEH]
Degradable plastic	Plastic Designed to undergo a significant change in its chemical structure under specific environmental conditions resulting in a loss of some properties that may vary as measured by standard test methods appropriate to the plastic and the application in a period of time that determines its classification. [ASTM and ISO]

Degradation	An irreversible process leading to a significant change of the structure of a material, typically characterized by a loss of properties (e.g. integrity, molecular weight, structure or mechanical strength) and/or fragmentation. Degradation is affected by environmental conditions and proceeds over a period of time comprising one or more steps. [ASTM, ISO, and CEN]
Die - Away test	Test method used for determination of "Ready" biodegradability. It is equivalent to Shake - Flask test and Sturm test. (See also Shake - Flask test)
Disintegrating	The falling apart into very small fragments of packaging or packaging material caused by a combination of degradation mechanisms. [ASTM, ISO, and CEN]
Ecotoxicity	Ecotoxicity refers to the potential environmental toxicity of residues, leachate, or volatile gases produced by the plastics during biodegradation or composting. [DEH]
Environmentally Degradable Plastic	A plastic designed to undergo a significant change in its chemical structure under one or combined environmental conditions mentioned above, resulting in a loss of some properties that may vary as measured by standard test methods appropriate to the plastic and the application in a period of time that determines its classification. [ASTM and ISO]
Head - Space test	Test method used for determination of "Inherent" biodegradability. The name comes from the sealed bottles with a headspace of air as an oxygen source (aerobic degradation) used in the test. Degradation is measured as a function of production of inorganic carbon (IC). It is equivalent to Concawe test.
Humus	The solid organic substance that results from decay of plant or animal matter. Biodegradable plastics can form humus as they decompose. Humus in soil provides a healthy structure within which air, water and organisms can combine. [DEH]
Hydrolytically degradable plastic	A plastic in which the degradation results from hydrolysis. [ASTM and ISO]
Kjeldahl Nitrogen method	This method for determining nitrogen content of organic and inorganic substances was first introduced by a German chemist, Johan Kjeldahl, in 1883. It comprises of three main steps: (i) digestion (breaking down of nitrogen in boiling sulfuric acid), (ii) distillation (condensation of NH_3), and (iii) titration.
Mineralisation	Conversion of a biodegradable plastic to CO_2, H_2O, inorganic compounds and biomass. For instance the carbon atoms in a biodegradable plastic are transformed to CO_2, which can then reenter the global carbon cycle. [DEH]
Oxidatively degradable plastic	A plastic in which the degradation results from oxidation. [ASTM and ISO]
Photodegradable	A process where ultraviolet radiation degrades the chemical bond or link in the polymer or chemical structure of a plastic. [DEH]
Photodegradable plastic	A plastic degraded by the action of natural daylight. [ASTM and ISO]
Semi - Continuous Activated Sludge (SCAS) test	A test method for determining "Inherent" biodegradability, originally developed by the Soap and Detergent Association for assessment of biodegradation of alkyl benzene sulphonate in an activated sludge environment, i.e. high concentration of microorganisms. The degree of degradation is determined as a function of the decrease of Dissolved Organic Carbon (DOC).

Shake - Flask test	Test method used for determining "Ready" biodegradability. The test is performed in conical flaks, which need to be shaken to maintain aerobic conditions. The degree of degradation is determined as a function of the decrease of Dissolved Organic Carbon (DOC). It is equivalent to Sturm test and Die - Away test.
Sturm test	Test method used for determination of "Ready" biodegradability. It is synonymous with Shake - Flask test and Die - Away test. (See also Shake - Flask test)
Zahn - Wellens method	A test method used for determining "Inherent" biodegradability. The percentage of degradation is determined as a function of Dissolved Organic Carbon (DOC) or Chemical Oxygen Demand (COD).

ASTM = American Society of Testing and Materials
CEN = European Committee for Standardization
DEH = Department of Environment and Heritage, Australian Government
DIN = Deutsches Institut für Normung
ISO = International Organization for Standardization
ISWA = International Solid Waste Association
1 = Online Chemistry Dictionary (http://www.chemistry-dictionary.com/Biodegradability)

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