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Critical Review of Norms and Standards for Biodegradable Agricultural Plastics Part II: Composting

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Abstract The critical review of norms and standards and corresponding tests to determine the compostability of biodegradable plastics, possibly applicable also to biodegradable agricultural plastics, shows that many norms concerning testing and labelling of compostable plastics have been established at the international level. Some of them are about plastic materials, some others are about products like packaging. The media and conditions of testing cover mainly the conditions designed for industrial composting facilities, and only a few concern home composting conditions. Considering that the end of life management of biodegradable agricultural plastic products will be done at the farm to reduce the management of the waste and also its cost, only a few of these norms are considered to be suitable for adaptation to cover also biodegradable agricultural plastic products. The biodegradability validation criteria under composting conditions, such as the threshold percentage of biodegradation and disintegration, the time and temperature, and the ecotoxicity, are presented for the main norms and standard testing methods. Based on these different norms and their content, a list of specs and technical requirements that could be adapted to meet farm composting conditions for agricultural compostable plastics is proposed. These requirements may be used as criteria for the establishment of a new integrative norm for agricultural compostable plastics.

Keywords Biodegradable agricultural plastics · Compostability at farm · Testing methods · Norms · Labelling

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Introduction

Biodegradable plastics are present today in various sectors of the economy; one of these sectors is agriculture. The global quantities of biodegradable plastics in use at the European Level in 2007 was about 30000 t, representing only 0.06% of the general plastics use of 47.5 Mt [1]. In France, for example, the corresponding figures are 6.7 Mt of plastic and 10000 t are biodegradable plastics, representing 0.15% of the use of plastics [2]. Biodegradable polymers are increasingly been used today as substitutes of plastics for several applications of conventional agricultural plastics [3–5], especially for developing agricultural films [6–8], but also plant pots, guide strings/clips for climbing plants, nets for agriculture and forestry (including animal net), compost bags etc. [9]. The use of biodegradable plastics for agricultural applications is not yet introduced widely in Europe, except for France where the biodegradable mulching film represents 3.6% of the mulching films in use [10].

The main reason for introducing biodegradable plastics in agricultural applications, even at a slow pace, is that the growing use of plastics in agriculture, which has enabled farmers to increase their crop production, is also associated with a major drawback: the problem with their disposal, following their useful life-time. Because of the wide use of agricultural plastics, the problem with the disposal of agricultural plastic wastes becomes more and more severe and rather complicated and expensive to solve [11–15]. Thus, specifically for the case of agricultural plastic wastes that cannot be easily collected and recycled (e.g. mulching films), one of the alternatives for their disposal is biodegradation. As a result, the use of biodegradable plastics is steadily expanding in the agricultural area with some products already in use (e.g. mulching films, developed experimentally and commercially [16–18]), while some new biodegradable products like pots or clips, have also been introduced in the market, but their use is still very limited. New biodegradable products that may be developed with biodegradable properties are also twines, low tunnel films (already developed experimentally [19]), wrapping film, trays, drip tape, etc. For the purpose of this paper, the study is limited to the biodegradable products that are to finish their life in the farm area, not considering the ones leaving the farm to the industries and customers, like biodegradable packaging materials, crates etc.

The management of biodegradable products used for agricultural applications is of concern mainly in terms of environmental impact, and should be evaluated in the framework of existing norms and standards for biodegradable plastics. Furthermore, the economic aspects should also be taken into consideration along with the fact that meeting the criteria set by norms for biodegradable materials is a marketing advantage for the product.

Biological treatment, e.g. composting or digestion, is an important method for the management of biodegradable plastic waste. International normalisation institutes have developed, or are in the process of developing, or revising, standard testing methods to confirm the biodegradability in various media or the compostability of materials and of products. In this context, concepts for characterisation, labelling and identification are being developed. Biodegradable plastics meet stringent norms with regards to their complete biodegradability, compost quality and product safety. Conformity with a standard can be declared by self-assessment or by third party certification. The European biodegradable plastics manufacturing industry is of the opinion that both biodegradable materials and the resulting compost product should be standardised [20].

Along this line, this paper (part II) presents a critical review of norms and standards and the corresponding testing methods to determine the biodegradability of biodegradable plastics in composting conditions, possibly applicable also to agricultural plastics that are characterised as compostable under farm conditions (part I presents the corresponding norms and standards for agricultural plastics characterised as biodegradable in soil [21]). The standardised criteria, parameters and testing methodologies for the characterization, labelling and validation of the agricultural plastic waste streams with respect to possible composting disposal alternatives according to existing international standards are analysed, while the controversies over the classification of biodegradable, compostable and disintegrable materials are identified. To derive the best suited for agricultural plastics specs and testing methods, the possible developments or adaptations of available specs or adoption of existing ones, are investigated. The goal is to consider the possibility of implementation of currently available characterisation standards, select the most appropriate tests for agricultural plastics and clarify the constraints and the limitations, and to propose modifications, especially with regard to simulating farm composting conditions.

Critical Review of Existing Norms and Standards for Testing Compostability

Norms and Standards for Testing Compostability

For biodegradable plastic materials to be accepted in composting plants, both biodegradability and disintegration are important. Disintegration is the physical falling apart of the biodegradable plastic material, or more precisely of the product that has been made from it, into fine visually indistinguishable fragments at the end of a typical composting cycle.

A compostable material is understood to be a material for which [22]:

- the polymer chains break down under the action of micro-organisms (bacteria, fungi, algae);
- total mineralisation is obtained (conversion into CO_2, H_2O, inorganic compounds and biomass under aerobic conditions); and
- the mineralisation rate is high and is compatible with the composting process.

Existing norms and standards on testing plastics for compostability have been reviewed. Table 1 presents a synthesis of the most important norms found for standards and tests for assessing compostability of plastics.

The norms presented in Table 1 are all about composting of plastic materials or they are devoted to products like packaging (e.g. the European norm). Some of these standards are key standard testing methods for characterising a material as compostable. Others are complementary or supporting documents for describing specific testing

Table 1 Norms for biodegradable plastic under composting conditions

American society for testing and materials international (ASTM)	
ASTM D6400-04	Standard specification for compostable plastics
ASTM D5338-98 (2003)	Standard test method for determining aerobic biodegradation of plastic materials under controlled composting conditions
ASTM D6002-96 (2002)	Standard guide for assessing the compostability of environmentally degradable plastics.
ASTM D6340-98	Standard test methods for determining aerobic biodegradation of radiolabeled plastic materials in an aqueous or compost environment.
ASTM D6003-96	Standard test method for determining weight loss from plastic materials exposed to simulated municipal solid-waste (MSW) aerobic compost environment.
ASTM D5509	Standard practice for exposing plastics to a simulated compost environment
ASTM D5512	Standard practice for exposing plastics to a simulated compost environment using an externally heated reactor
ASTM D5988	Standard test method for determining the aerobic biodegradation in soil of plastic materials or residual plastic materials after composting
ASTM D5951	Standard practice for preparing residual solids obtained after biodegradability standard methods for toxicity and compost quality testing—fate & effect testing
International organization for standardization (ISO)	
ISO 17088:2008	Specifications for compostable plastics
ISO 14855-1:2005	Determination of the ultimate aerobic biodegradability of plastic materials under controlled composting conditions—method by analysis of evolved carbon dioxide—part 1: general method
ISO 14855-2:2007	Determination of the ultimate aerobic biodegradability of plastic materials under controlled composting conditions—method by analysis of evolved carbon dioxide—part 2: gravimetric measurement of carbon dioxide evolved in a laboratory-scale test
ISO 16929:2002	Plastics—determination of the degree of disintegration of plastic materials under defined composting conditions in a pilot-scale test.
ISO 20200:2004	Plastics—determination of the degree of disintegration of plastic materials under simulated composting conditions in a laboratory-scale test.
European committee for standardization (CEN)	
EN 13432-2000	Packaging—requirements for packaging recoverable through composting and biodegradation—test scheme and evaluation criteria for the final acceptance of packaging
EN 14995-2006	Plastics—evaluation of compostability—test scheme and specifications
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 14806:2005	Packaging. Preliminary evaluation of the disintegration of packaging materials under simulated composting conditions in a laboratory-scale test.
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 ISO 20200:2005	Plastics—determination of the percentage disintegration in a laboratory composting environment
Deutsches Institut für Normung (DIN)	
DIN V 54900-1998	Prüfung der Kompostierbarkeit von polymeren Werkstoffen
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 ecotoxicity 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.

Table 1 continued

Italian Norm (Italian Unification Agency) (UNI)	
UNI EN 14995-2006	Plastics—evaluation of compostability—test scheme and specifications
Japanese industrial standard	
JIS K 6953-2000	Determination of the ultimate aerobic biodegradability of plastic materials under controlled composting conditions—method by analysis of evolved carbon dioxide
Belgium standard	
Belgium Royal decree (9/09/2008) effective in July 2009	Decree specifying the norms that the products should meet to be compostable or biodegradable

methods and evaluation procedures, included in the main standard testing methods.

The key compostability characterisation norms set the requirements for polymers to be recoverable through composting and biodegradation, including the test scheme and evaluation criteria for the final acceptance of polymers as compostable. To comply with these standards a product must possess the ability to undergo a complete biological decomposition due solely to the action of naturally occurring micro-organisms. In these different norms, the oldest supplying the latest, three common validation criteria of the compostability have been identified: the plastic conversion to CO_2 and biomass, the plastic fragmentation or disintegrability, and the plant growth on the compost (and a threshold limit for regulated metals). In the different norms the tests reproduce the process of well run municipal composting facilities.

Main ASTM Norms for Characterising Compostable Plastic Materials

The ASTM's Committee D20 on plastics [23] has developed the ASTM D6400 [24] standard *"Standard Specification for Compostable Plastics"* to cover products claiming to be biodegradable via composting. The issue of the first version of ASTM D6400 in May 1999 represents a major milestone, as it was a turning point in the development of the industry of biodegradable plastics. The standard ASTM D6400 is intended to *establish the requirements for labelling of materials and products, including packaging made from plastics, as "compostable in municipal and industrial composting facilities.*" This standard establishes criteria (specifications) for plastics and products made from plastics to be labelled as compostable. It determines if plastics and products made from plastics compost satisfactorily, including biodegrading at a rate comparable to known compostable materials (i.e., food stuffs, lawn wastes, and paper). Further, the properties in the specification are required to assure that the degradation of these materials will not diminish the value or utility of the compost resulting from the composting process. The standard identifies three criteria: complete biodegradation, disintegration, and safety as shown in Fig. 1.

ASTM D6400 addresses the compostability of plastic materials, and standard specifications and terminologies for biodegradable plastics as well as guidelines for using specific test methods. In particular, ASTM D6400 is based on and references three other ASTM D20 standard documents for the testing and identification of plastics that will biodegrade and compost satisfactorily. They are:

ASTM D6002, guide for assessing the compostability of environmentally degradable plastics—outlines recommended procedures and a general approach to establish the compostability of plastics [25]. It provides a three-tiered criteria-based approach that includes rapid screening tests, laboratory and pilot scale composting assessment, and field/full scale assessment.

ASTM D5338, test method for determining aerobic biodegradation of plastic materials under controlled composting conditions [22]—determines the degree and rate of aerobic biodegradation of plastic materials on exposure to a controlled-composting environment under laboratory conditions. This is achieved by mixing the plastic with stabilized and mature compost derived from the organic fraction of municipal solid waste. The aerobic composting takes place in an environment where temperature, aeration and humidity are closely monitored and controlled. The plastic must completely mineralize—convert to CO_2, water, and biomass—via microbial assimilation. This test method is designed to yield a percentage of conversion of carbon in the sample to carbon dioxide. The rate of biodegradation is monitored as well. The net production of CO_2 is recorded relative to a control containing only mature compost. After determining the carbon content of the test substance, the percentage biodegradation is calculated as the percentage of solid carbon of the test substance converted to CO_2. In addition to carbon conversion, disintegration and weight loss can be evaluated.

ASTM D6340, test method for determining aerobic biodegradation of radio-labelled plastic materials in an aqueous or compost environment [26]—determines the rate and degree of biological oxidation of carbon in plastic

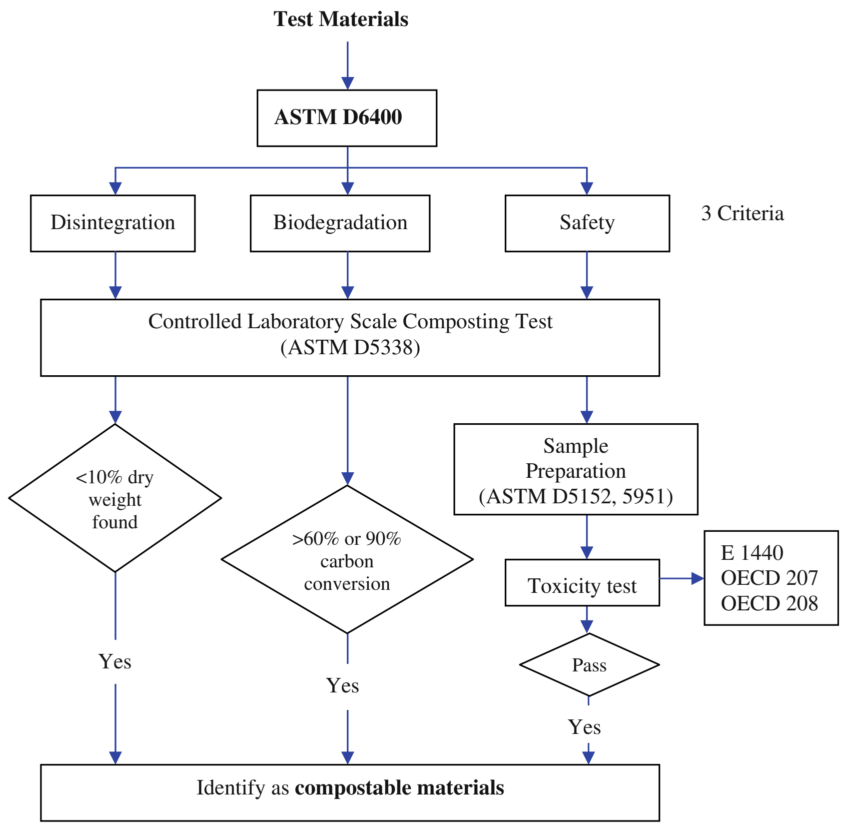

Fig. 1 Compostable materials identification flow chart according to ASTM D6400 [95]

materials when placed in a composting environment containing simulated municipal solid waste or an aqueous environment under laboratory conditions. It applies to plastics the biodegradation rate of which is slow and requires test periods of as long as 365 days.

Apart from the above four standards, some additional supplementary ASTM standard testing methods relevant to testing compostability of plastics are also presented in Table 1 [27–31].

ASTM Standard Criteria (Specifications) for Plastics and Products Made from Plastics to be Labelled as Compostable

The key requirements set by the ASTM standards for labelling of materials and products, including packaging made from plastics, as "compostable in municipal and industrial composting facilities", may be described briefly as follows (ASTM D5338 standard [22]):

- Sixty percent of single polymer materials must mineralize in up to 6 months
- Polymer blends, copolymers, and plastics with low-molecular weight additives or plasticizers must show 90% biodegradability in the same time frame.
- Materials in product form must show intense microbial activity and be converted from carbon to carbon dioxide, biomass and water. They must disintegrate into fragments with less than 10% of the material being caught on 2-mm sieves.
- Finally, after land application, remaining materials must not be toxic or limit plant growth. Regulated (heavy) metals content in the polymer should be less than 50% of EPA (U.S., Canada) prescribed threshold. Ecotoxicity tests are carried out in accordance with ASTM D6400 to certify that it is compostable.

Main ISO Norms for Characterising Compostable Plastic Materials

The International Standards Organization (ISO) ISO/TC 61 is the International Committee responsible for Plastic standards. Under this committee biodegradable plastic International Standards are in development in Subcommittee 5, Working Group 22. These Standards are in harmony with the ASTM, CEN (European), and DIN (German) Standards. Several Standards have been issued and more are under development. The main issued ISO Standards relevant to characterising compostable plastic materials are:

The ISO 17088:2008 [32] standard specifies procedures and requirements for the identification and labelling of plastics, and products made from plastics, that are suitable for recovery through aerobic composting. This ISO standard, in an analogous way with the ASTM D6400 standard, is based on and references two other ISO standard documents for the testing and identification of plastics that will biodegrade and compost satisfactorily:

ISO 14855-1:2005 determination of the ultimate aerobic biodegradability of plastic materials under controlled composting conditions—method by analysis of evolved carbon dioxide—part 1 [33]: This norm specifies a method for the determination of the ultimate aerobic biodegradability of plastics, based on organic compounds, under controlled composting conditions by measurement of the amount of carbon dioxide evolved and the degree of disintegration of the plastic at the end of the test. The main method uses a solid-phase respirometric test system based on mature compost used as a solid bed, a source of nutrients, and an inoculum rich in thermophilic microorganisms. The test method is designed to yield the percentage conversion of the carbon in the test material to evolved carbon dioxide as well as the rate of conversion. However, it can be difficult to quantify the residual polymeric material left in the bed at the end of the test, to detect possible low-molecular-mass molecules released into the solid bed by the polymeric material during degradation, and to assess the biomass. As a result, it can be difficult to perform a complete carbon balance. Another difficulty which is sometimes encountered with mature compost is a "priming effect": the polymer-induced degradation of the organic matter present in large amounts in the mature compost, which affects the measurement of the biodegradability. Also specified is a variant of the method, using a mineral bed (vermiculite) inoculated with thermophilic microorganisms obtained from compost with a specific activation phase, instead of mature compost. This variant can be used to measure the biodegradation in terms of CO_2 evolution and the rate of conversion, to quantify and analyse the biomass and the residues of polymeric material left in the solid bed at the end of the test, and to perform a complete carbon balance. Furthermore, the method is not sensibly affected by the priming effect and can, therefore, be used to assess materials known to cause this problem with mature compost. The mineral bed can also be subjected to an ecotoxicological analysis to verify the absence of any ecotoxic activity in the bed after biodegradation.

ISO 14855-2:2007 determination of the ultimate aerobic biodegradability of plastic materials under controlled composting conditions—method by analysis of evolved carbon dioxide—part 2: Gravimetric measurement of carbon dioxide evolved in a laboratory-scale test [34], specifies a method for determining the ultimate aerobic biodegradability of plastic materials under controlled composting conditions by gravimetric measurement of the amount of carbon dioxide evolved and the amount of compost and sample used.

Apart from the above three ISO standards, two additional complementary ISO standard testing methods relevant to testing compostability of plastics are also presented in Table 1:

ISO 16929:2002 plastics—determination of the degree of disintegration of plastic materials under defined composting conditions in a pilot-scale test [35]. This standard is part of the evaluation of the compostability and biological treatability of plastics as indicated in ISO 15986. This International Standard is used to determine the degree of disintegration of plastic materials in a pilot-scale aerobic composting test under defined conditions. Disintegration of plastic materials is specified by the requirement that at least 90% of the plastic must fragment to particles <2 mm in size in composting within 12 week composting test.

ISO 20200:2004 specifies a method of determining the degree of disintegration of plastic materials when exposed to a laboratory-scale composting environment. ISO 20200, or equivalent, is performed in aerobic aqueous environment or soil. The method is not applicable to the determination of the biodegradability of plastic materials under composting conditions. Further testing is necessary to be able to claim compostability.

ISO Standard Criteria (Specifications) for Plastics and Products Made from Plastics to be Labelled Compostable

ISO 14855-1 gives similar guidelines to that of ASTM D5338 [22], but there are some technical differences which are presented in a next section on the comparison between available standards.

Main European Norms for Characterising Compostable Plastic Materials

The European Commission (EC) and the European Free Trade Association have mandated the development of Standards for Biodegradable Packaging Materials. This is under the jurisdiction of CEN TC 261 (packaging)/SC4 (packaging and environment)/WG2 (degradability and compostability) [36], the secretariat of which is held by AFNOR. The key specification, test scheme, and guidelines are detailed in EN 13432:2000/AC: 2005, packaging—requirements for packaging recoverable through composting and biodegradation—test scheme and evaluation criteria for the final acceptance of packaging [37]. This European Standard supports essential requirements of EU Directive(s) and forms one of a series of standards and reports in support of the European Council and Parliament Directive on Packaging and Packaging Waste [94/62/EC]. This norm is a reference point for all European producers, authorities, facility managers and consumers. Unlike the ASTM standards, this standard can be applied to any packaging or packaging component, and is not limited to plastic materials.

For a material to pass the standard EN 13432, it must not persist for longer than 6 months under any of the conditions stipulated in the above tests and have a pass level of 90%. In addition, the material must not exceed heavy metals content above 50% of that for 'normal' compost.

The European Commission (EC), in addition to EN 13432 for packaging materials, has also mandated the development of Standards for Biodegradable Plastics under composting conditions. The standard EN 14995-2006 'plastics—evaluation of compostability—test scheme and specifications' [38], has been prepared by the Technical Committee CEN/TC 249 "Plastics", the secretariat of which is held by IBN/BIN. This European Standard defines the requirements for plastic materials to be considered organically recoverable. It provides a framework which can be used to support claims of compostability of plastics. The approach of this European Standard is comparable to that of EN 13432 which defines the requirements for packaging materials.

The EN 13432:2000/AC:2005 standard and the EN 14995-2006 standard, in an analogous way with the ASTM D6400 standard and the corresponding ISO 17088:2008, specify the four requirements and procedures establishing the composting nature of packaging, or plastics, respectively. The four requirements and procedures, covering the same scope as ASTM's three criteria, are themselves specified in other standards.

1. Biodegradability (ISO14855, EN 14046).
2. Disintegration during biological treatment (EN 14045)
3. The absence of negative effects on the process of biological treatment
4. The absence of negative effects on the quality of the resulting compost and a low level of heavy metals.

The standard EN 14046:2003 'packaging—evaluation of the ultimate aerobic biodegradability of packaging materials under controlled composting conditions—method by analysis of released carbon dioxide' [39] was developed under the directive area of "Packaging and packaging waste 94/62/EC", by CEN/TC 261 [36]. This standard is equivalent to the standard ISO14855 described above (EN ISO 14855:2004 [40]; Determination of the ultimate aerobic biodegradability and disintegration of plastic materials under controlled composting conditions—method by analysis of evolved carbon dioxide).

The EN 14045:2003 'packaging—evaluation of the disintegration of packaging materials in practical oriented tests under defined composting conditions' [41], describes the analysis of packaging disintegration under industrial composting conditions.

Apart from the above EN standards on compostability, two additional complementary EN standard testing methods relevant to testing compostability of plastics and packaging are also presented in Table 1:

EN 14806:2005 Packaging. Preliminary evaluation of the disintegration of packaging materials under simulated composting conditions in a laboratory-scale test [42].

EN ISO 20200:2005 plastics—determination of the percentage disintegration in a laboratory composting environment [43].

These two methods are not applicable to the determination of the biodegradability of plastic materials and packaging under composting conditions. Further testing is necessary to be able to claim compostability.

EN Standard Criteria (Specifications) for Plastics and Products Made from Plastics to be Labelled as Compostable

Plastic products can provide proof of their compostability by successfully meeting the harmonised European standard, 13432 [37] and EN 14995 [38]. The European Packaging Directive 94/62 EC makes reference hereto with regard to compliance with the EN 13432. The standards EN 13432 [37] and EN 14995 [38] give some similar technical guidelines to that of ASTM D5338 [22], but there are also technical differences.

The scope of testing plastic materials under EN 13432 [37] and EN 14995 [38] is to ensure that a compostable packaging or plastic material, respectively, must have the following characteristics:

- Biodegradability, which is determined by measuring the actual metabolic conversion of the compostable material into carbon dioxide (oxygen consumption and production of CO_2). This property is quantitatively measured using the standard test method, EN 14046 [39], which is also published as ISO 14855: biodegradability under controlled composting conditions [44, 45]. The acceptance level is 90% (as referred to cellulose), which must be reached in less than 6 months (conditions are optimised at 58 °C, with closely monitored and controlled humidity at around 50%, and proper air circulation to maintain the oxygen concentration above a minimum of 6%).
- Disintegrability, that is, the fragmentation and loss of visibility in the final compost (absence of visual contamination). This is measured with a composting test (EN 14045; described below). The test material is degraded, together with organic waste, for 3 months.

After this time, the compost is sieved with a 2 mm sieve. The residues of the tested material with dimensions higher than 2 mm are considered as not having disintegrated. This fraction must be less than 10% of the initial mass.

- Quality of compost: absence of negative effects on the composting process. This is checked with a composting test: practical test of compostability in a semi-industrial (or industrial) composting facility: No negative influence on the composting process is permitted (this is checked with a composting test in a semi-industrial, or industrial, composting facility; EN 13432 [37]).
- Ecotoxicity of compost application: Low levels of heavy metals (below the previously established threshold levels), and absence of negative effects on the quality of the compost. A plant growth test (OECD test 208, modified [46]) is carried out on compost samples where the degradation of the test material has taken place. There must be no difference in plant growth from a control compost sample. Other chemical-physical parameters that must not be different from those of the control compost after the degradation are the pH, salinity, volatile solids, N, P, Mg, K. Chemical tests are performed to disclosure of all constituents, threshold values for heavy metals are to be adhered to. In characterization, the packaging materials (or plastics) are analyzed to determine the composition, the presence of hazardous substances (e.g., heavy metals), organic carbon content, and total dry and volatile solids. To pass the evaluation criteria on the chemical characteristics, the packaging material must have those values within specifications listed in Annex A.1 of EN 13432 [37]. For example, packaging, packaging materials, and packaging components should contain at least 50% of volatile solids, and the concentration of heavy metals should not exceed the values listed in the table of the maximum heavy metal content of packaging material and whole packaging from EN 13432, Annex A1 [37] (note: 'Volatile solids' means the materials that become volatile at high temperatures; a temperature of 550 ± 50 °C is used for an ignition test as described by ASTM D5338 [22] and the American Public Health Association (APHA) standards [47]).

The maximum material gauge of a plastic is determined by its compostability in standard practice composting operations. All tests must be passed. Success in individual tests will not be sufficient. The EN standard test methods are based on the scientific definitions of several ISO standards: ISO 18451 [48], ISO 18452 [49] (aerobic degradability in water), ISO 18453 [50] (anaerobic degradability in water) and ISO 18455 [44, 45] (aerobic composting). The tests must be conducted by recognized test laboratories.

Each of the points described above is necessary for the definition of compostability, but these alone are not sufficient. For example, a biodegradable material is not necessarily compostable because it must also break up during one composting cycle. On the other hand, a material that breaks up, over one composting cycle, into microscopic pieces that are not totally biodegradable, is not compostable. To precise this fact a flow chart is built in the norm and explains the chain of criteria that the product should pass to be considered as compostable.

Italian National Norms for Characterising Compostable Plastic Materials

In Italy a previous standard (UNI 10785 [51]), concerning the compostability of plastics (Requirements and test methods), was recently replaced by its European version (UNI EN 14995: plastics—evaluation of compostability—test scheme and specifications) [52]. This new standard specifies the requirements and procedures for the determination of compostability or the anaerobic treatment of plastic materials with reference to the following characteristics: biodegradability, disintegration during biological treatment, effect on quality of the resulting compost. It does not apply to plastic packaging, that is considered in a specific Standard (UNI EN 13432) [53].

UNI 11183 [54]: A national norm dealing with requirements and test methods for plastic materials to be considered biodegradable at room temperature. The scope of this norm is to describe the conditions for cold composting testing and the criteria of validation for acceptance of the tested product as home compostable. The reference standard is ISO 17556 [55] or ISO 14855 [33, 34] but with some changes. There is a preparation of the sample, to have a thickness of particles under 180 µm or a film thickness under 20 µm (without thermo degradation, use of liquid nitrogen for fragmentation). The test is run first in soil medium (ISO 17556 [55]), at temperature between 21°C and 28°C, and if the biodegradation in a year is 90% or over the product is considered biodegradable (at ambient temperature) otherwise it shall be considered as not biodegradable. If the relative biodegradation of the material is between 60 and 90% a supplementary test is required. The supplementary test on this specific material is run in compost condition (ISO 14855 [33, 34]) for six months, and the product will be considered as biodegradable if 90% of biodegradation is achieved.

German National Norms for Characterising Compostable Plastic Materials

In Germany for biodegradable plastics to be accepted in compost operations and satisfy the German Green Dot system requirement (i.e. Duales System Deutschland GmbH (DSD) [56]), the plastic will have to pass the DIN V 54900 "Testing of the compostability of plastics" [57]. DIN V 54900 (replaced by DIN EN 13432 [58]) is similar to the CEN standard EN 13432 and it is a three tiered testing protocol (like the ASTM D6002). It has the same strict pass/fail requirements of the CEN standard—requiring complete biodegradability and disintegration to become an integral part of the compost. A product certification from DIN-CERTO (an affiliate of the DIN Standards Organization) would be needed—third part validation. As the DIN norms (as well as the BS, UNI and other national norms) adopt the corresponding EN standards, no further analysis is carried out concerning national standards.

Belgian Royal Decree for Acceptance of Compostable and Biodegradable Plastic Materials

In Belgium, very recently (9 September 2008) a royal decree was published [59] to present the characteristics that a product should meet to be compostable or biodegradable. The products that biodegrade in water medium are excluded of the norm. The decree becomes effective in 9 months after its publication, so in July 2009. The novelty of this decree is to distinguish three possible properties for three end-of-life management options: Compostable, Home compostable and Biodegradable. For compostable products, the royal decree establishes that the products have to respond to the CEN standard EN 13432 [37]. For biodegradable products the material has to respond to NF U52-001 [60] and no pre-treatment with light or temperature are accepted. For home compostable products (all type of compost done at home except worm composting) the norms are the ISO Norms 14851 [48], 14852 [49], 14855 [44, 45] and 17556 [55], but with a temperature between 20 and 30 °C. The rate of biodegradation for home composting of the products should be 90% (in weight compared to cellulose) in 12 months maximum without any pre-treatment.

Comparison Between Main International Norms for Characterising Compostable Plastic Materials

ASTM D6400 [24] is comparable or in harmony with standards in Europe, Japan, Korea, China, and Taiwan. The specifications set by the ASTM D6400 standard along with the three references standards presented above, are comparable (but not the same) to what has been developed by the European Committee for Standardization (CEN) in Europe, and in harmony with the relevant ISO standards for compostable plastics, moving the industry closer to global standards.

The Standard EN 13432 [37] is very similar to the ASTM D6002 [25], except that it has pass/fail specifications built into it. The key specification, through the testing method described by EN 14046 [39], is the requirement of >90% biodegradability for blends, copolymers etc., as measured by ISO 14855 (controlled composting) test method [33, 34].

The biodegradation test described in ISO 14855 [33, 34] is similar to the test method in ASTM D5338 [22], with a few differences. First, the ISO test method does not require the negative control vessels; therefore, only 9 vessels are required instead of 12. Second, ISO 14855 [33, 34] also includes the determination of percentage of biodegradation based on weight loss as an optional result to support the value determined from carbon dioxide evolution. Third, the acceptance level of percentage of biodegradation of the test material is at least 90% in total or 90% of the maximum degradation of the reference material after a plateau stage for both reference and test materials has been reached.

Biodegradability is determined by measuring the amount of CO_2 produced over a certain time period by the biodegrading plastic. The main point of differentiation between the various international standards is the percentage of biodegradation required for compliance. ASTM D5338 [22] standard requires 60% biodegradation of homopolymers within 180 days and 90% for blends while the ISO standard requires 90% biodegradation within 180 days for any product. The ISO 14855-1 [33] standard and the European Norm EN 13432 [37] are stricter than the ASTM standard. Furthermore there are on-going discussions on revising the European Norm EN 13432 [37] (and EN 14046 [39] and possibly ISO 14855-1 [33]) so that it requires 90% biodegradation within 90 days instead of 180 days [61]. This is an important issue that is under discussion at ISO level. The compliance requirements for the key standards are shown in Table 2.

According to ISO 14855-1 [33], the mineralization of an unknown biodegradable material should be 90% of the value obtained for a reference material to prove its biodegradability. In both ISO 14855-1 [33] and ASTM D5338 [22] methods, the amount of CO_2 evolved due to biodegradation can be measured using acid–base titration, or by using a direct measurement such as infrared or gas chromatography. ISO 14855-2 [34], which measures mineralization of a polymer by a gravimetric method, is similar to 14855-1 [33] except for the method of CO_2 measurement and the amount of compost and sample used. In addition, inert materials such as sea sand or vermiculite can be used with the compost for providing better aeration and retention of moisture content. The mixture of compost and sea sand or vermiculite is periodically taken out from the closed system to turn or agitate to prevent channelling of air in the biodegradation vessel.

Furthermore, while the temperature profile is continuously at 58 °C in both ISO 14855 [33, 34] and the CEN test procedures, it follows a temperature profile of 35–58–50–35 °C in the ASTM D5338 test [22].

Table 2 Standards Compliance Requirements under controlled aerobic composting conditions

Standard	Method	Biodegradation requirement (mineralisation)	Temperature	Time frame to achieve biodegradation requirements (months)
ASTM D5338 [22]	Analysis of evolved carbon dioxide.	60%[b] (of single polymer; relative to a control containing only mature compost)[a] 90% must do so in blends	A cycle with the following temperature profile : 35–58–50–35 °C	6
ISO 14855-1 [33]	Analysis of evolved carbon dioxide.	≥90% (in total or 90% of the maximum degradation of the reference material)	58 °C	6
EN 14046 [39]	Analysis of evolved carbon dioxide.	≥90% (compared to cellulose control/ reference material)	58 °C	6[a]

[a] There are different opinions on this and suggestions to amend the EN 14046 standard to 90% biodegradation within 90 days; A proposal was made also to amend the EN 13432 [33] standard to 90% disintegration within a maximum of 12 months. As a compromise, extension of the timescale could be accompanied by a reduction of the temperature at which the tests are carried out—from 58° to 38° [61]

[b] There are discussions for the 60% theoretical biodegradation of homopolymer to be deleted; 90% would be acceptable [93]

An important part of assessing biodegradable plastics is testing them for disintegration in the form in which they will be ultimately used. Either a controlled pilot-scale test or a test in a full-scale aerobic composting treatment facility can be used. The disintegration of the test material is evaluated on the basis of the total dry solids by comparing the retrieved fractions of the test material >2 mm and the amount tested (it is measured by sieving the material to determine the biodegraded size: less than 10% in weight should remain on a 2 mm screen for most standards). The compost obtained at the end of the composting process can be used for further measurements such as chemical analyses and ecotoxicity tests. Due to the nature and conditions of such disintegration tests, the tests cannot differentiate between biodegradation and abiotic disintegration,[1][62–65] but instead demonstrate that sufficient disintegration of the test materials has been achieved within the specified testing time. For disintegration, the European and ISO standard suggest testing the materials in controlled pilot-scale and full-scale tests, as described in ISO 16929 [35], instead of using the controlled laboratory-scale test in ASTM D6400 [24]. But the rest is similar, i.e., the final compost is screened with a 2 mm sieve, and the material needs to pass the disintegration criterion (i.e., no more than 10% of the original dry weight is recovered after 12 weeks of composting according to EN 13432 [37] and ISO 16929 37]).

Ecotoxicity of compostable plastics is measured by having concentrations of heavy metals below the limits set

Table 3 Maximum heavy metal content for compostable materials according to various standards [93]

Element (mg/Kg d.w.)	ASTM D6400 [24]		EN 13432 [37]	Japan
	US	Canada		
Zn	1400	925	150	150
Cu	750		50	60
Ni	210	90	25	30
Cd	17	10	0.5	0.5
Pb	150	250	50	10
Hg	8.5	2.5	0.5	0.2
Cr			50	50
Mo		10	1	
Se	50	7	0.75	
As	20.5	37.5	5	5
F			100	
Co	75	75		

by the standards and by special testing methods. The methods of the evaluation of the ecotoxicity of compostable polymer materials are mainly based on the use of plants, soil fauna (earthworms), aquatic fauna (Daphnia), algae (green algae), microbes (luminescent bacteria) [66]. The corresponding provisions differ between the various standards as presented in Table 3.

ASTM and ISO standard guidelines are limited to the biodegradability evaluation (biodegradation, disintegration, compost quality) of plastic material or a plastic material from a package; however, the standards EN 13432 [38] and EN 14995 [38] developed by the European Committee for Standardization (CEN) provide detailed guidelines for evaluation of biodegradability and compostability of packaging and packaging components, and plastics, respectively, based on their characterization, biodegradability,

[1] Abiotic degradation may be induced by UV or thermal in dry or humid conditions, water, salt solution etc. The ASTM D6954, Tier 1, BS 8472 and ISO 4611, ISO 4892-2 Standards define the requirements for abiotic degradations as follows:

Average molecular, weight Mw <10 000, gel fraction <5%, elongation at break ≤5% of the original value.

disintegration, and compost quality/ecotoxicity. For the compost quality or ecotoxicity test, physical and chemical parameters such as density, total dry and volatile solids, salt content, and pH, have to be determined to show that the tested packaging does or does not have negative effects on the compost quality. Only the plant growth test, based on OECD guideline 208, [46] is included in EN 13432 [37] for ecotoxicity. The results (germination numbers and plant biomass) of the compost with the tested material and the blank compost are compared.

In general, for a comprehensive assessment of toxicity associated with compost applications, plastics can be tested on both plant and animal species, as required by the corresponding norms (e.g. EN 13432 [37]: plant growth test) and/or chosen by the interested parties. Toxicity screening of some commercial degradable plastics using animal cell culture testing has been reported in [67]. Concerning plant phytotoxicity testing, while a product may not negatively impact plant growth in the short term, over time it could become phytotoxic along plant development due to the build-up of inorganic materials within determined parts of the plant, which could potentially lead to a reduction in soil productivity [68]. For this reason some manufacturers use plant phytotoxicity testing on the finished compost that contains degraded polymers [68]. Typically, summer barley is used in toxicity testing to represent monocots and cress to represent dicots. Tests involve measuring the yield of both of these plants obtained from the test compost and from control compost. Animal testing is generally carried out using earthworms (soil organisms) and Daphnia (aquatic organisms). The Daphnia toxicity test is used to establish whether degradation products present in liquids pose any problem to surface water bodies. Earthworms are used because they feed on soil and they are very sensitive to toxicants [69]. Earthworms are exposed to several mixture ratios of compost and soil mixtures. Following 14 days of exposure, the number of surviving earthworms is counted and weighed and the survival rate is calculated (test of acute toxicity within 14 days (mortality) (OECD 222 [70]); chronic toxicity (reproduction) 56 days (OECD 207 [69])). Compost worms (Eisenia fetida) are used for testing the toxicity of biodegradable plastic residues. These worms are very sensitive to metals such as tin, zinc, heavy metals and to high acidity [68, 71]. For this test worms are cleaned and accurately weighed at intervals over 28 days.

Comparison of Norms with Low Composting Temperature

The international standards and norms for composting are based on, or reproduce, the industrial composting facilities conditions; that is to say, the temperature for the test is commonly set at 58 °C. But in case of the agricultural products the end of life management will be probably done at the farm and so the composting will not be made in the way it is applied in industrial or municipal compost facilities; it will induce lower temperatures and probably a lower biodegradation rate of the products [61, 72, 73]. At a national level standardization, the framework for home (farm) composting has been identified in a few cases. The corresponding national standards framework is interesting and seems more related to real farm management of agricultural biodegradable plastics. At least two norms are dealing with home (farm) composting: The Italian norm UNI 11183 (Plastic Materials Biodegradable at ambient temperature. Requirements and test methods) [54], concerns testing of biodegradation and ecotoxicity without disintegration, applicable to Mesophilic phase (ambient temperature at 10–45 °C) in a fertile soil medium. The testing methods employed by this standard are based on ISO 17556 [55], 14851 [48], 14852 [49] (365 days, 21–28 °C). Belgium has also recently published a Royal Decree establishing product standards for compostable and biodegradable materials (official journal 24/10/2008; Belgium Royal decree specifying the norms that the product should meet to be compostable or biodegradable) [74]. The products are certified and labelled, when meeting the corresponding requirements, as ‘OK Compost’, ‘OK Compost HOME’ or ‘OK Biodegradable SOIL’.

The low temperature composting norms criteria are presented in Table 4. An agreement is observed in biodegradation rates and the corresponding time frame and also on the range of possible temperatures for these tests.

Future Developments

Based on the above, it should be clear that the procedure to have any package or plastic certified as ‘compostable’ is very elaborate. It involves not only the package or plastic passing the test method ASTM 5338 [22] or ISO 14855 [33, 34] or EN 14046 [39] but also meeting various other requirements, such as passing the disintegration test, having levels of heavy metals within limits, and passing the plant growth test by having no significant difference on plant growth between the compost containing test material and the blank compost.

Biodegradation of biodegradable packages in real composting conditions, has been reported and correlated to visual changes and to variations in the physical properties of the materials [75]. Real composting studies give clear representation of the biodegradability nature of the whole package configuration and the time required for the disintegration in different compost recipes and composting processes. This information can further provide a basis for deciding on compostable packaging materials and the planning of composting processes. Real composting

Table 4 Low temperature composting norms conditions

Standard	Method	Biodegradation Requirement (mineralisation)	Temperature	Time frame to achieve biodegradation requirements (months)
UNI 11183	Analysis of evolved carbon dioxide.	≥90% (in total or 90% of the maximum degradation of the reference material)	21–28 °C	12
Belgian Royal decree (9/09/2008) effective in July 2009	Analysis of evolved carbon dioxide.	≥90% (in total or 90% of the maximum degradation of the reference material)	20–30 °C	12

conditions are governed by the outer atmosphere, the type of compost, and the compost parameters such as temperature, moisture and pH. As a result, they may differ from the controlled composting conditions proposed by the ASTM, ISO and EN standards for materials and whole packages. As new standards for assessment of biodegradability of materials are becoming available, and usage of biodegradable plastic packages increases, there is a need to establish a reliable method which would give a clear understanding of the biodegradability of a package or plastic material with respect to the time required for disintegration and the efficiency of disposal to justify its compostability [75]. According to [75] there has not been any study done which compares biodegradability in real and simulated conditions.

Critical Presentation of Schemes for Labelling Materials as Compostable

Labelling and Certification Schemes for Compostable Packaging and Compostable Plastic Materials

Currently, there is confusion in the market about conventional plastics and biodegradable and compostable plastics, since these materials are hardly physically distinguishable by the user. Furthermore, many composters are still sceptical about the ability of the plastics claimed to be compostable, to biodegrade in their facilities. To succeed in recovering these materials and properly composting them, there must be a widely accepted labelling system that clearly distinguishes them from the conventional materials and guarantees their compostability. Identification and labelling are two of the most critical factors in the future growth of the compostable products market. In order to claim or label a product or package as compostable, or biodegradable, there should be reliable scientific evidence to support this claim. In addition, there must be a certification concerning the composting conditions, since plastic materials or packages that are compostable in specific facilities (e.g. industrial facilities) may not be compostable in home composting, because of different composting conditions, such as the waste mixture, moisture content, and temperature.

Therefore, certification is the first step to have compostable packages and plastic materials identified and accepted by composting facilities. Organizations such as the Biodegradable Products Institute (BPI) [76], the U. S. Composting Council (USCC) [77], the European Bioplastics [78] and DIN CERTCO, or the certification organization of the German Institute for Standardization [79], offer certification programs, that award a compostable logo to approved products. This is achieved through specific labelling schemes.

The BPI Labelling Scheme

BPI in cooperation with the USCC uses the ASTM specifications D6400 [24] and D6868 ''Standard Specification for Biodegradable Plastics Used as Coatings on Paper and Other Compostable Substrates'' [80]. The compostable BPI logo (Table 5) is given to products that are compliant with ASTM specifications based on testing results from any approved laboratory.

The Association "European Bioplastics" Labelling and Certification

The association European Bioplastics [78] (the former IBAW Interest Group for Biodegradable Materials) calls to approve plastic products according to EN 13432 [37], or respectively EN 14995 [38], if the marketer advertises the product to be "compostable" or "biodegradable". In addition, in an effort to avoid the confusion resulting from the incorrect use of the terms "degradable" or "oxo-degradable" plastic products as being equivalent (or alternative) to the terms "compostable" or "biodegradable", the association has published relevant clarifying information [21, 78]. Producers have signed a voluntary self commitment on product certification which has been acknowledged by the European DG Enterprise. DIN CERTCO [79] operates a certification scheme for compostable products made of biodegradable materials and licenses the use of the corresponding 'compostable' logo (Table 5) developed by European Bioplastics [78].

Table 5 Labelling and certification systems for compostability [94]

Certification organisation	Logo	Testing according to standard
Din Certco (germany) and IBAW International Biodegradable Polymers Association and Working Group		EN 13432/DIN V 54900
AIB Vinçotte (Belgium)		EN 13432 ISO 14851 ISO DIS 17566.2; ISO 11266; ASTMD.5988-96
Jätelaitosyhdistys (Finland)		EN 13432 ISO 14851
US Composting Council and BPI Biodegradable Product Institute		ASTM 6400
BPS Biodegradable plastic Society (Japan)		GreenPla certification Program ISO 14851 OECD 301C JIS K 6950, 51, 53

Certification by DIN CERTCO [79] is an integral part of an industrial recycling system. It enables compostable products to be identified by a unique mark and channelled for recovery of their constituent materials in specially developed processes. The Compostability Logo (also referred to as DIN CERTCO Mark) thus conveys product information to waste-disposal plant operators, and the environmental friendly image (concept) of the product to consumers. With this currently developed version of the DIN CERTCO [79] certification scheme, a certification can be conducted according to two well accepted standards: DIN EN 13432 [37] and ASTM D6400 [24]. Laboratory tests have only to be performed separately for materials, intermediates and additives used for the particular product(s) under certification. In these tests the chemical properties are checked, the ultimate biodegradability is verified, and the disintegration properties are determined. Chemical testing verifies that neither harmful organic substances, such as polychlorinated biphenyl (PCB) and dioxins, nor heavy metals, such as lead, mercury or cadmium, pass into the soil via the compost. The methods specified for the testing of biodegradability and of disintegration are applied to verify the complete degradation of the materials within the processing period of normal composting plants, but not for home composting conditions. Also, the non toxicity test is applied according to the standards. Additionally the maximum compostable layer thickness is determined. If the results of the tests are in conformity with the standard(s) and/or the certification scheme, the material, intermediate or additive is registered and included in a positive, with respect to compostability requirements, list. Products that have been manufactured of registered compostable materials (i.e. they are included in the positive list), intermediates and additives, may be certified directly without additional testing, if they meet the maximum compostable layer thickness of the used materials or intermediates.

Other Compostable Materials Labelling Schemes

Many other organizations also certify compostable materials based on DIN EN 13432 [37] and ASTM D6400 [24] or both. For example, AIB Vincotte (AV) [81], located in Belgium, awards the 'OK compost' logo (Table 5)). The United Kingdom adopted the EN 13432 [37] standards as well (BS EN13432) for compostable packaging materials. Among the certification bodies across the European Union, included is 'The Composting Association' in the United Kingdom. This Association operates a certification program in cooperation with the German certifier, DIN CERTCO [79]. Other certification bodies award certificates (not compostable labels) to products that meet ASTM, ISO, or CEN standards, similar to the ISO 9000 series certification. For example SGS [82] offers biodegradability and ecotoxicity testing based on ISO standards. The Finish and the Japanese labelling schemes are based on the EN 13432 and the Japanese JIS K 6950, 51, 53 standards, respectively (Table 5)).

Internationalisation of Labelling Schemes

While technical differences still do exist between the major standards and labelling schemes, harmonization efforts are under way at ISO level. DIN and the BPI have already signed a memorandum of understanding to work towards harmonization and mutual recognition of each other's certification programs. The end result of such efforts is that manufacturers will be able to bring products to market more rapidly and cost effectively.

The Italian Approach on Labelling Materials as Compostable

The growing interest in environmental matters, and in particular, in interventions designed to contribute to the control of the climatic changes resulting from greenhouse gas emissions, is creating a new market for products and services that are genuinely eco-compatible. Essential to this new economic parameter is the adoption of a series of instruments that measure, control and check the environmental performance in various applications, including agricultural applications.

An important contribution to the environment, which could be considered as a first basis for a scheme for labelling materials as compostable, may derive from the promotion of the Environmental Product Declaration (EPD) [83], a factor considered strategic for verifying the true environmental benefit of using biodegradable plastic polymers. The EPD is an important voluntary instrument for qualifying companies that intend to take an active role in managing the environmental factor. The EPD enables communicating the environmental contents of a product, both objectively and transparently. The presence of recognised rules, of a qualified and authoritative managing body, and of a reliable validation system, is essential element to guaranteeing and protecting EPD use. The major Italian producer of bioplastics, Novamont, was recently invited to take part in one of the pilot projects set up by the Italian environmental protection agency, ANPA, making its skills and data available for defining the product specific requisitions (PSR) for plastic materials, and for all related assessments.

To quantify the different impact on the environment a comparison between a compostable product against a conventional one should be done with a Life Cycle Assessment (LCA). This approach would be really helpful for the users to validate also the environmental benefit (or not) of a biodegradable product. It is clear that the choice for a biodegradable product by the end-user is not only based on its biodegradable properties but also considering the environmental impact of the product.

Adaptation of Existing Norms for Labelling and Certification Scheme for Agricultural Compostable Plastics

The possible adoption of the European norms EN 13432 [37] and EN 14995 [38] for compostable packaging and for compostable plastic materials, respectively, for labelling agricultural compostable packaging and agricultural compostable plastic materials, has some advantages and disadvantages.

Advantages

These are the main European norms that solve the problem of misusing the terms *"biodegradable material"*, *"biodegradation"* and *"compostability"* by defining the characteristics a material or a product must own in order to be claimed as *"compostable"* and so, recycled through composting of organic solid waste [21]. This is very important as materials that are incompatible with composting may decrease the final quality of the compost and therefore its commercial value and applicability.

These norms represent the basic European framework for testing and labelling, through the corresponding "seedling" labelling scheme, compostable packaging and plastic materials. They therefore represent the main reference norms for the producers, public authorities, composting plant managers, and the consumers. The "seedling" labelling scheme activities and the corresponding norm EN 13432 [37], were initially developed for packaging because of the large quantities of packaging waste and the associated cost of treatment. The agricultural biodegradable plastics, having no specific labelling stream, theoretically could reach the labelling stream of compostable packaging. However, as the new norm EN 14995 [38] became already available for compostable plastics in general, within the "seedling" labelling scheme, the "seedling" labelling scheme is considered to represent an appropriate scheme also for compostable agricultural plastics. The advantage is that compostable agricultural plastic products may be certified according to the European norm EN 14995 [38] and be labelled through the "seedling" labelling scheme.

Disadvantages

At present, it is not common to find products, among the biodegradable products in use in agricultural field, having their end of life management in compost (more than 95% of biodegradable agricultural plastics is mulching film for which the end of life is biodegradation in soil) [21]. The possible compostable agricultural products are clips and twines to stake the "climbing" plants like tomatoes, cucumbers, etc. The practice with greenhouses tomatoes cropping is to be removed at the same time and pull out: plants, twines, clips (Fig. 2).

In addition, even if agricultural biodegradable products have their end of life management in compost the norm testing conditions at the farm (58 °C, adjust moisture content and air flow), will be very difficult to accomplish. To produce « good » compost is not an easy task. The composition, size of particles, moisture and air flow regulation, have to be optimised and monitored [84]. So, even if the product is compostable according to the EN 13432 [37] or EN 14995 [38], as applicable, the composting at the farm will not probably give the results of the norm tests. Composting under farm conditions is expected to lead to a lower biodegradation rate that is not comparable with the EN 13432 [37] or EN 14995 [38] predictions. Another validation of composting properties will be needed if the management of compost by farmers is only building a pile of the waste (the most common practice), A validation analogous to what is commonly known as home composting or another version of it (farm composting) needs to be established.

Proposed Universal Compostability Specs for Agricultural Plastic Waste

Development/Adaptation of Composting Specs for Agricultural Plastic Waste

Targeted pre-normative research is needed on developing a specific norm and labelling scheme for "farm composting" of compostable plastic products (including agricultural compostable plastic products) so that they are labelled accordingly. This will give the appropriate framework for agricultural and other compostable products ending their life in home or farm compost. The enterprise AIB Vinçotte [81] has already created the labelling "OK compost home" [74] to respond to the demand of manufacturers of biodegradable products. In an analogous way, a specific norm and labelling scheme for compostable products in farm may be developed possibly adapting/revising the "seedling" scheme.

Another issue is that till now, all tests and standards are used on thin materials (<100 μm) like films or powder of material. For example, a film is certified 'OK Compost' by AIB Vinçotte [81] for a given maximum thickness. There is no certainty that a thicker film will disintegrate within the prescribed periods. The German certifier, DIN CERTCO [79] applies a procedure where testing is not performed with the starting material (granule), but with test samples of defined thickness, e.g. films. The goal is to determine the maximum thickness of the material that can be completely decomposed within one composting cycle. This maximum decomposable thickness determines the maximum thickness for products that can be certified according to this DIN. Testing is conducted in a practical test using a composting system with low technical standards as well as in a technical trial that is intended to simulate a system

Fig. 2 Pictures of compostable plastic clips and strings during and after greenhouse tomato crop

with high technical standards [85]. However, there are also biodegradable materials used in agricultural applications like clips, strings, etc. (Fig. 2) that are much thicker than thin films. No results on biodegradation tests of these materials have been reported in the literature and no provision is offered by the standard testing methods on handling these materials. This is another area of research to develop in the future.

Regarding the specificity of the agricultural plastics, preference should be given to developing a home/farm compost test that is better adjusted with the end of life management of agricultural compostable products, so that the specific test and labelling refers to the products and not only to its components like the "resin". Such a specific norm and labelling scheme, better adjusted with the end of life management of agricultural compostable products at the farm, may be developed by possibly adapting/revising the "seedling" scheme. To conclude on the scheme for labelling of agricultural products as compostable at farm, it is proposed that an adapted labelling scheme is developed through:

- Development of specific testing methods for the composting conditions of agricultural products at the farm (compost components, temperature, moisture, aeration, thickness of products) also considering thick compostable materials, through targeted pre-normative research. A relevant topic with a project on norm development in Italy recently ended up to a new Official Standard (UNI EN 11355:2010 Plastic items biodegradable in home composting—requirements and test methods [86]). This standard defines the requirements to be met by plastic items that can be disposed of through composting household, also called cold composting, through aerobic biodegradation at room temperature. The term "ambient temperature" is intended to indicate the temperature range of temperate regions, excluding the high temperatures typical of industrial composting. This standard takes into account the biodegradable materials at room temperature according to UNI 11183 [54], and establishes criteria for items that, made of these materials, are compostable at home composting systems. In this standard the requirements of biodegradation and ecotoxicity are not taken into consideration as they are already covered by UNI 11183 [54] in reference to materials (resins) used as raw materials for manufacturing the tested items.
- Development of a specific labelling scheme for the agricultural compostable at farm products that may be incorporated in the existing labelling schemes.
- Co-normative research in support of the development of a European Norm for farm compostable products at the European Level (EN), possibly (or partially) based on the principles of the Belgian royal decree and the Italian discussion team on home compostable products.

A Synthesis of Proposed Specs

From the elements presented above, some common specifications for composting streams are identified, and specific specs are proposed for agricultural compostable plastics:

Common Specs

- No pre-treatment of materials or used products for tests (like exposure to UV light or heating for a predefined period before testing the samples for biodegradation).
- Limits in heavy Metals and toxic substances content (adopt the corresponding specs of EN 13432 [37] and EN 14995 [38])
- Limits in persistent organic pollutants (NF U52-001 [60]) as shown in Table 6.
- No ecotoxicity on higher plants growth, on earth worms, on green algae (ISO/DIS 11269-2 [87], ISO 11268-1 [88], NF T90-375 [89, 90]).
- Volatile solids: Plastic materials shall contain a minimum mass of 80% of volatile solids which exclude largely inert materials (NF U52-001 [60]).
- exemption for the equivalent form (UNI EN 14995 [52])
- recording of assessment outcome (UNI EN 14995 [52])

Table 6 Limits in persistent organic pollutants according to NF U52-001 [60]

Organic pollutants	Maximum concentration mg/kg of dry mater	Maximum cumulative quantities in 10 years duration period g/ha
Main 7 PCB's (PCB 28, 52, 101, 118, 138, 153, 180)	0.8	4
PAH, Fluorathene	4.0	20
PAH, benzo(b) Fluorathene	2.5	12.5
PAH, benzo(a) Fluorathene	1.5	7.25

Specific Specs for Biodegradation by Industrial Composting

- Biodegradation rate of 90% (in comparison to cellulose) in six months of industrial composting conditions (58 °C).
- Disintegration in twelve weeks, not more than 10% of the original dry weight of the plastic material shall fail to pass through a 2 mm fraction sieve (EN 13432 [37] and EN 14995 [38]).
- A question has been raised concerning the need for an overall carbon balance taking into account both the carbon immobilized as biomass and that volatised as CO_2 in assessing the compostability of plastics. According to the work of [91] there is some evidence that biodegradation in soil of carbon substrates with low free-energy content (i.e. a high level of oxidation) as measured only by net CO_2 evolution could be overestimated to some extent. However, as most of the carbon of the material is released as CO_2 as the microorganisms use the carbon mainly to generate chemical energy for their life processes by biologically oxidizing it to CO_2, complete biodegradation needs to be documented by 90+% of the carbon in the product being converted to CO_2 by the microorganisms [92] (considering also a ±10% statistical variability of the experimental measurement). This strict requirement given in [92] implies that the carbon of the material is predominantly, at least in most cases, converted to CO_2 and the immobilization forms are normally not significant. This is also why all the existing tests of biodegradability focus on measuring the CO_2 evolution as a "measure" for the evaluation of biodegradability.

Specific Specs for Biodegradation at Home and/or Farm Composting

- Composting of the biodegradable plastic product in its commonly used form at removal (no requirement for specific grinding).
- Biodegradation rate of 90% (in comparison to cellulose) in a year of farm composting conditions (20–30 °C) for thin films based on the Belgian royal decree for home composting.
- A biodegradation rate (in comparison to cellulose) in 6 months or in a year of farm composting conditions (30 °C) has to be defined after experiences for clips, pots and other products thicker than 100 μm
- Composting the products with farm crop residual as usual.

Conclusions

This review has shown that many norms concerning testing and labelling of compostable plastics have been developed at national and international level. Some are about plastic materials others about products like packaging. The media and conditions of testing cover mainly the conditions designed for industrial composting facilities, and only a few concern home composting conditions. To reduce the management of the waste and also its cost, the end of life management of biodegradable agricultural plastic products will be done most frequently at the farm. Only a few of the existing norms will be suitable, after appropriate revisions, to be adapted to testing biodegradable/compostable agricultural plastic products.

The biodegradability validation criteria under composting conditions, such as the threshold percentages of biodegradation and disintegration, the time and temperature, and the ecotoxicity, have been presented for the main norms and standard testing methods. Based on those different norms and their content a list of specs and technical requirements that could be adapted to meet farm composting conditions for agricultural compostable plastics is proposed. These requirements may be used as criteria of the establishment of a new integrative norm for compostable plastics used in agricultural applications.

Targeted pre-normative research is needed on developing a specific norm and labelling scheme for "farm composting" of biodegradable agricultural compostable plastic products so that they are labelled accordingly. This should include the development of specific testing methods for the composting conditions of agricultural products at farm, also considering thick compostable materials. It should also include the development of a specific labelling scheme for the agricultural products compostable at farm that may be incorporated in the existing labelling schemes.

A comparative Life Cycle Assessment for the compostable agricultural plastic products against the corresponding conventional plastic products needs also to be performed, to assess the global environmental impact of these products.

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