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Sustainable Food Packaging: Materials and Waste Management Solutions

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The current food packaging model in most cases is a linear material flow model and is far from the sustainable alternative – circular economy – approach where materials are recycled and recovered at the end of each service life. High concern is rising on packaging waste and especially plastic packaging and negative environmental impact. A number of factors, including policy and legislative changes, rising concerns on food and packaging waste, environmental contamination, and world demand for food and energy resources, undoubtedly make an impact on development of biodegradable and compostable packaging made from renewable environment friendly resources and a sustainable waste management opportunity at the end of product life. Food packaging industry already has options of compostable packaging that meets biodegradation and composting standards and does not impact environmental contamination, but a variety of existing bio-labels such as *biobased*, *biodegradable*, and *compostable* appear misleading for consumers, and terms *biodegradable* and *compostable* are often used as synonyms, although they are not the same.

Keywords: biodegradable package, compostable package, food packaging, food packaging waste, plastic packaging.

Introduction

A food production and consumption cycle is a complex process in which food waste and food packaging waste management at the end of the life cycle plays significant role. Annual food waste volumes in the European Union (EU) are around 100 million tons, of which approximately one third (30%) goes to the agri-food supply chain (Gustavsson et al., 2011). Because of the growing population and growing food demand (based on prognoses, food demand will increase up to 50%), these numbers are likely to rise to over 200 million tons by 2050 (Scialabba, 2013). This will definitely increase packaging waste volumes, mainly those of paper and plastic. Paper and cardboard (41%) as well as plastic (19%) are the most common types of packaging waste in the EU-27 (Eurostat, 2020). Among plastic packaging, poly-ethylene (PE) is the most commonly used polymer (Singh et al., 2014).

According EU statistics, 23 million tons of plastic packaging are produced annually, and in 2050 this number is expected to reach 92 million tons (Plastics Europe, 2015). Plastic packaging waste raises the biggest concerns on environmental impact, so far as 40% of disposable (single use) or very short usage food packaging ends up in a way which has a negative environmental impact, i.e., landfilling. This inefficient end-of-life scenario of packaging corresponds to 9 million tons of plastic accumulated in soils decreasing soil and whole food chain quality (Guillard et al., 2018). As much as 32% leak out of collecting and sorting systems and finally end in the soil and ocean as well. If production and use continue within the current linear framework, worldwide, by 2050, the plastic industry will represent 1,124 million tons of plastic materials (Rosentrater et al., 2019). Recycling or reusage of conventional plastic packaging wastes should become priority in waste management. Higher recycling or reusage rates will not only reduce fossil fuel, which is used in conventional plastic production, but will also make a positive environmental impact on global climate change reducing CO_2 emissions (Tuladhar and Yin, 2019). Another sustainable packaging waste management solution based on circular economy principles is biodegradable and compostable packaging.

The aim of this article is to review the food packaging waste situation in the European Union, sustainable food packaging solutions available on the market and materials they are made from, paying special attention to plastics and bioplastics products. Differences between *biodegradability* and *compostability* will also be indicated as well as clear distinctions between terms of *biobased, biodegradable* and *compostable* will be highlighted.

Packaging waste sustainability approach

Packaging role and innovations demand

Packaging covers several functions: safety, protection, hygiene and others. The main one is to protect the product and prevent/minimize product waste. Next to product safety and waste prevention, shelf life, hygiene and health are considered very crucial as well. Packaging should ensure high product hygiene norms, especially for food and beverages, and extend healthy product life (Emblem and Emblem, 2013). Innovative sustainable packaging must meet all these (and many more) requirements. In the recent decade, special attention has been paid to the innovative materials packaging and sustainable waste management solutions. Some existing food packaging is innovative and sustainable by its resources and is biobased, some is innovative and sustainable by its end of life and is biodegradable or compostable. However, full and fair assessment of the overall environmental benefits needs to be done (Guillard et al., 2018). Unquestionably, innovative biobased packaging can become a great alternative for traditional conventional plastic packaging. However, despite many publications, research and development analyzing environment friendly biobased, biodegradable and compostable materials, commercial availability does not yet properly meet producers and consumers demands (Rosentrater et al., 2019).

Sustainable food and packaging waste management

As mentioned before, around 100 million tons of foods in the EU are wasted per year. According to food waste classification, food waste is attributed to the bio-waste category. Bio-waste is defined as biodegradable waste such as green garden or park waste. It also includes food leftovers and kitchen waste from households and catering service providers, food waste from retail premises, and comparable waste from food processing plants. Another, also biodegradable, waste category includes paper and cardboard, natural textiles, processed wood, forestry or agricultural residues, manure, and sewage sludge. These products are counted as biodegradable, but they are not attributed as bio-waste. The bio-waste category also excludes those by-products of food production that never become waste (European Commission, 2019).

The amount of packaging waste is growing, and according to Eurostat data, 31.2 million tons of packaging (made of paper and cardboard) waste was generated in 2017. Plastic packaging numbers take a second place based on volumes. Plastic packaging reached 14.5 million tons of waste in the same year (Eurostat, 2020). As mentioned before, plastic and paper / cardboard are most common types of packaging waste. Increasing packaging waste volumes cause significant environmental impacts starting from consumption of primary raw materials and ending with large amounts of disposal followed by a huge amount of waste that ends up in landfills or as litter. Sustainable waste management and mitigation of negative environmental impacts of food waste and food packaging waste are complex and interconnected processes. It is necessary to consider the environmental impact of primary raw packaging material, take into consideration available solutions to mitigate the environmental impact of food loss and analyze sustainable food and packaging waste management system.

In the product life-cycle, handling and disposal of food packaging after the end of its life cycle play a significant role. Different environmental impacts are caused by the packaging disposed at landfills compared with the recycled packaging. As a sustainable waste management way, including food waste and food packaging waste (compostable), composting has become an attractive option and an important component in a waste management strategy. Materials of a biological origin have a lower environmental footprint compared with those made from fossil fuels. Compostable packaging products made from renewable resources can divert significant amounts of waste, which ends up in landfills or is incinerated. The main advantages replacing conventional plastic packaging to compostable ones include (Shen et al., 2009):

- conservation of fossil fuel, which is the main material in conventional plastic production;
- mitigation of climate change caused by CO_2 emissions;
- improvement of organic waste management, i.e., composting instead of landfilling.

Biodegradation and composting principles

Biodegradable vs compostable

Recent concerns in biodegradability and compostability of packages have been raised mainly because of the environmental issues caused by conventional plastics industry. The demand for biodegradable and compostable packaging products is rapidly increasing. It is important to note that terms *biodegradable* and *compostable* are often used as synonyms, but they are not the same. All compostable materials naturally biodegrade, but not all materials that biodegrade are suitable for composting. *Biodegradable* does not mean that the material is compostable or even recyclable. Composting is a process with specific conditions (such as temperature, moisture, oxygen) and environment where biodegradation occurs. The biodegradation process is defined by the environment and the timeframe. The timeframe aspect is important as most of the materials are able to biodegrade in natural environment but it might take 10, 15 or even more years to do so and that is why the composting process is framed with a timeframe and environmental conditions. Determination of composting criteria is also important because materials that are not suitable for composting can reduce the final quality of compost (Muscat et al., 2012).

Biodegradation

Biodegradation has a strong potential in reducing food and food packaging waste. Biodegradation is a natural disintegration process of organic waste into primary elements existing in nature (CO2, water and biomass) by microorganisms such as fungi, bacteria or yeast. Biodegradation is often defined as an event which occurs via the action of enzymes and/or chemical decomposition associated with living organisms, such as bacteria, fungi, etc. (Zhong et al., 2020). The biodegradation process can occur in the environment with and without oxygen; in other words, it can be aerobic or anaerobic. In the aerobic treatment process, natural microbial colonies use oxygen as the electron acceptor to convert organic substances into water. The by-products of the aerobic process are 5 moles of carbon dioxide, 3 moles of water and an increased population of microorganisms (Eskander and Saleh, 2017).

Anaerobic treatment is a set of biological processes in which microorganisms disintegrate organic biodegradable materials in the absence of oxygen. Oxygen used by microorganisms in anaerobic biodegradation is substituted by nitrate, sulphate, iron, manganese or CO2. These compounds act as the electron acceptor, and as by-products include nitrogen gas, hydrogen sulphide, a reduced form of metals, and methane, depending on the electron acceptor (Eskander and Saleh, 2017).

Composting

Composting is an enhanced biodegradation process under managed conditions (such as concrete timeframe, moisture, oxygen) characterized by forced aeration and natural heat production as a result of biological microorganism activities inside organic compost material. The final product – compost – is rich in nutrients and is often used as a fertilizer to improve quality of the soil. Thus, composting requires material not only to biodegrade, but also to become part of usable compost and provide the soil with nutrients (European Parliament, 2018).

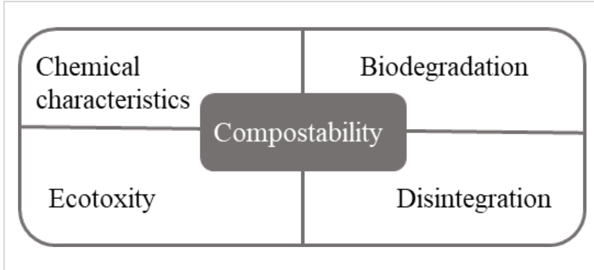
Composting is a process where decomposition occurs when micro-organisms start breaking down organic materials into the final product, i.e., compost. Biodegradation is a completely autonomous usually longer lasting process, while composting is framed in time and requires additional human management.

Composting as well as biodegradation can be aerobic and anaerobic. Degradation of materials in the composting process with provided oxygen is called aerobic treatment. Degradation of materials in the composting process without oxygen, like in the biodegradation process, is anaerobic.

The difference between aerobic and anaerobic composting is methane production. Methane is produced only under anaerobic conditions. Similarities of both processes are production of carbon dioxide and water.

To summarize, compostability compared with biodegradation is a combined process with specific characteristics under specific conditions, with a process managed by humans, and the final result is compost. The compostability process should be evaluated under 4 characteristics (De Wilde et al., 2013) illustrated in Figure 1.

Fig. 1. *Overview of the main characteristics required for industrial compostability. Source: (De Wilde et al., 2013)*



Environmental impact and quality of the final product are described under chemical characteristics and ecotoxity. Biodegradation and disintegration describe degradation characteristics of the process of composting. Disintegration is a physical material decomposition after the complete composting cycle into visually indistinguishable fragments (up to 2 mm). The biodegradation process ends up with a complete breakdown of organic materials to minerals and products (De Wilde, 2002). There is also an official certification system, international standardization and certain requirements that compostable materials have to meet.

Plastics. Origin and biological treatment

Compostability standard

A compostable plastic is biodegradable in a composting environment (State Department of Ecology Olympia, 2013), yielding water, CO2, biomass, and inorganic compounds. As mentioned before, the end product – compost – must meet environmental and biodegradation requirements (Figure 1), visually disintegrate up to 2 mm (EN 14045), and not to have any toxic footprint which could make a negative impact of compost and soil quality. In order for a plastic (as well as other organic compostable materials) to be labeled as compostable, concrete scientific requirements under the standard EU 13432:2000 must be met (ASTM International, 2012):

- Disintegration: no more than 10% of the residues from the packaging waste fragments after sieving on a 2 mm sieve after 84 days in controlled composting test.

- Mineralization: the biodegradation level of at least 90% must be reached in less than 6 months, either from bio-waste and packaging like paper products and biodegradable plastics.
- Eco-toxicity: the product must have less than 50% of the maximum allowable concentrations of certain heavy metals regulated by biosolids. Compost must also be able to support germination of two different plant species at a rate at least 90% of that in a "control" sample.

Many researches indicate that the biodegradability does not depend on the raw material but entirely on the chemical structure of the polymer chains (Chanda, 2017). It is important to note that compostable plastics can be plant based but they can be petroleum based as well, and in this case, the environmental aspect plays a crucial role because of the controversial and often negative environmental impact of fuel-based biodegradable plastics.

Plastics: biobased, biodegradable and compostable

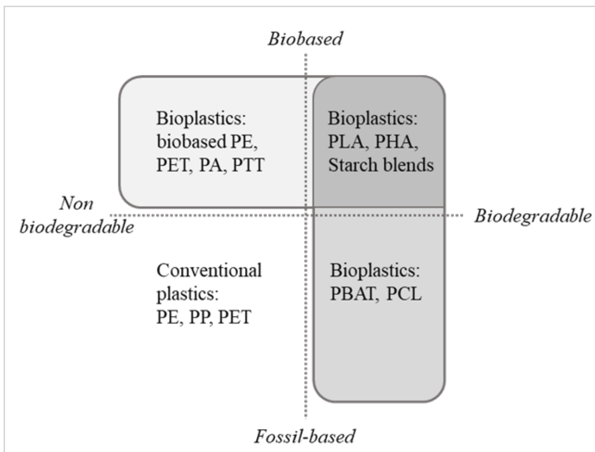
A number of various bioplastic products have emerged on a market over the past years labeled with different labels such as *biobased, biodegradable,* and *compostable*. And this variety of existing bio-labels appears misleading for consumers. Often it becomes unclear whether the product is recyclable or compostable. Does it fit for home composting, is it naturally biodegradable, or is it only for industrial compost production? Most of the current market biodegradable plastics (such as PLA) biodegrade only under specific industrial composting conditions and do not meet home composting requirements; neither these plastics decompose under natural conditions in a reasonable timeframe when littered. And even more – the environmental impact is questioned as damaging consequences for fauna and flora might occur, for example, aquatic ones (European Commission, 2011).

The term *biobased* means that production material is (or at least partly) derived from biomass – plants not from fossil fuel (European Bioplastics, 2020). The most common biomass source for bioplastics production is corn, sugarcane, or cellulose. The term *biodegradable* means that material the product is made from at the end of its life can naturally biodegrade. Biodegradable materials can either be made from natural renewable resources or be fossil based. The main feature of a biodegradable product is its end of life, i.e., availability to biodegrade. Biodegradable packaging products are divided into fiber-based packaging and bioplastics (Aryal, 2019).

Bioplastics, according to the European Bioplastics Association, are the plastics made from biomass (raw material – biomass) or are biodegradable (end of life – biodegradable). Bioplastics can have both mentioned features, i.e., be biobased and biodegradable. Compared with fossil fuel-based conventional plastics, biobased plastics are often considered a much more advanced packaging material with significantly less carbon footprint and with more sustainable waste management options, such as composting (European Bioplastics, 2020). Three main groups of bioplastics families are shown in Figure 2:

- fossil based biodegradable plastics (e.g., PBAT);
- biobased, i.e., made from biomass or partly from biomass, which is not biodegradable (e.g., PE, PP, PET, PTT);
- biobased and biodegradable (e.g. PLA, PHA, PBS).

Fig. 2. *Bioplastics family. Source:(European Bioplastics, 2020)*



As mentioned before, bioplastics can be made of biomass or be fossil based but the origin does not mean that material is biodegradable or compostable.

Whether a material can biodegrade or be accepted at a compost facility depends on its chemical structure and whether this material can be a food source for bacteria, fungi, and algae in a set environment and timeframe, as well as if a compost facility will accept them (Department of Ecology Washington state, 2014). However, the quality of the compost (if material is compostable) and the environmental impact of fossil-based bioplastics remain an issue. As an alternative bio-packaging material, biopolymers, i.e., semi-synthetic polymers made of renewable biomass, are considered as an advanced option, which allows packaging materials to be biodegradable or compostable completely (Zhonga et al., 2020).

In the recent years, research has focused on innovative material development, such as bioplastics from organic waste. One of the main goals of new material development is to eliminate negative externalities of current plastic packaging and create the circular economy concept that does not compete with food usage. Agricultural and agri-food residues could be turned into naturally biodegradable packaging materials with a fair and transparent eco-efficiency performance assessment (Rosentrater et al., 2020).

While innovative material (with no negative environmental impact) research is still undergoing a project phase, currently biodegradable bioplastics are typically single use or short life packaging such as tableware like cups, plates, take away food containers or food waste collection bags. Some of these products are promoted as suitable for composting at the end of life (Thompson, 2009). While biobased bioplastic products made from food resources, such as corn, potatoes, rice, soy, sugarcane, wheat, and vegetable oil, are facing different opinions supporting positive and negative aspects of biobased bioplastics, there are opinions that biobased bioplastics contribute to an increase in food security concerns and pressure on agricultural land (Putri, 2018). Controversial opinions on a negative environmental impact on PLA appear as this material fits only for the industrial composting and contributes to complicating the waste management: separate collecting and sorting of these materials are thus needed (Emadian et al., 2017). While we are facing many different arguments and opinions, Wageningen Food & Biobased Research in February 2020 (Van der Zee and Molenveld, 2020) published the observed disintegration rate of compostable plastics (certified according to the current standard EN 13432) and sufficiency to be compatible with the current separately collected post-consumer organic waste (further in the text GFT) treatment practice in the Netherlands.

Compostable plastics research and results

In the period February–October 2019, Wageningen Food & Biobased Research, commissioned by the Dutch Ministry of Economic Affairs and Climate Policy (EZK), carried out the research (Van der Zee and Molenveld, 2020) with the main core to analyze plastic products and their fulfillment of the requirements for compostable packaging (according to standard EN13432) in a full scale of organic waste treatment facility. An organic waste treatment trial was performed at Van Kaathoven (Valor), Sint Oedenrode, Netherlands, which is one of the treating source facilities of separated municipal organic waste. The process for executed organic waste treatment and compost production is schematically presented in Figure 3.

The organic waste treatment ran in a controlled tunnel composting system and was operated according to the normal operation, i.e., composting for 11 days (one organic waste treatment cycle) with active aeration from below and spraying moisture from above. A set of 9 different compostable plastic products (coffee pads and capsules, tea bags, fruit labels, waste collection bags and plant pots) from various producers were selected based on the sorting protocol provided by Elsinga and Wageningen Food & Biobased Research laboratory (Van Velzen et al., 2018), following these criteria: diversity in type of plastic, diversity in base material, commercial availability, demonstrated compostability (i.e., certified according to EN 13432), expected co-benefits (i.e., increased collection rates, decreased contamination). The organic waste treatment trial consisted of two separate parts and ran in the same tunnel composting facility at the same treatment time and under the same treatment conditions:

a Identification of the fate of selected products in full scale biological treatment, following selected compostable products during the organic waste treatment process and identifying in which (residual) fractions the products would likely end up. Substantial amounts (see Table 1 for number added to organic waste (A)) of compostable products were introduced into collected post-consumer organic waste. Two organic waste treatment runs (11 days each) were executed.

b Disintegration of test products in mesh bags, evaluating the disintegration of selected compostable products under the regular operation conditions and timeframe (in relation to the results obtained with laboratory testing required for certification according to EN13432). Substantial amounts of test products (see Table 1 for number added to organic waste (B)) were mixed with recently collected source separated municipal solid organic waste and put in 50 L mesh bags. After the first organic waste treatment cycle (11 days), the mesh bags were opened for visual inspection. After the second organic waste treatment cycle (11 days), disintegration was analyzed sieving the content of mesh bags with the set of sieves (10 mm, 8 mm, 4 mm and 2 mm). Visible fragments of the test products were retrieved manually from each fraction, weighed, and photographed.

Fig. 3. *A schematic presentation of the organic waste treatment process at the Van Kaathoven (Valor) facility, location Sint-Oedenrode. Dashed arrows indicate that the residual fractions (3) and (5) are occasionally (but not always) recirculated. Source: (Van der Zee and Molenveld, 2020)*

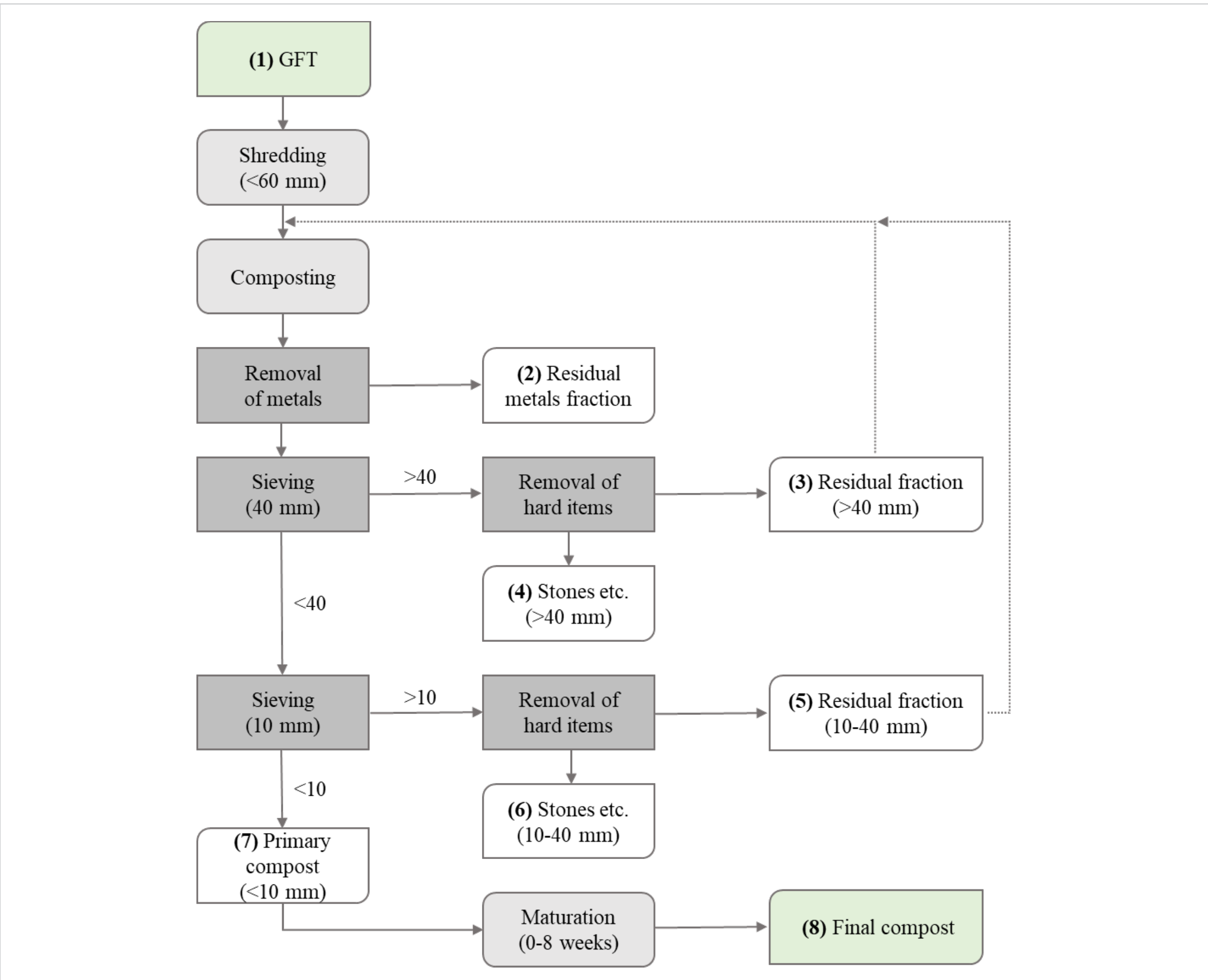


Table 1. *Waste treatment trial products, final qualification of the disintegration rate and risk of ending up in discarded residue fractions or contaminating the final compost. Source (Van der Zee and Molenveld 2020)*

Code	Product	Composition. *Number added to organic waste (A) / mesh bag (B)*		Risk of ending up in discarded residue fractions	Risk of visual contamination of compost
A	GFT collection bag Compostability certificates: OK compost IND: TA8011300630 OK compost HOME: O16-1859-A Compostable (Seedling): 7P2018	Thermoplastic starch with biodegradable polyester. *1000 / 10*	+	Low	Low
B	GFT collection bag Compostability certificates: OK compost IND: TA8011601461 OK compost HOME: TA8021601496	Thermoplastic starch with biodegradable polyester. *1000 / 10*	+	Low	Low
C	Plant pot Compostability certificates: Compostable (Seedling):	Thermoplastic starch with biodegradable polyester. *300 / 5*	++	Low	Low
D	Plant pot (cuttings) Compostability certificates: OK compost IND: TA8011500968	PLA. *500 / 10*	+++	Low	Low
E	Teabag (used) Compostability certificates: Compostable (Seedling):	Paper and PLA fibres. *590 / 50*	++	Low	Low
F	Fruitlabel Compostability certificates: OK compost IND: TA8011903519 Compostable (Seedling): 7H2020	Biodegradable polyester coated paper. *1000 / 75*	++	Low	Low
G	Coffee capsule (used) Compostability certificates: OK compost IND: O17-2386-B	PLA with biodegradable polyesters. *1000 / 50*	+	Low	Possibly
H	Coffee pad (used) Compostability certificates: Compostable (Seedling): 7P2096	Paper and PLA fibres. *1000 / 50*	++	Low	Low
J	Teabag (used) Compostability certificates: Compostable (Seedling): 7P2174	PLA filter and thread, PLA coated tag. *1000 /50*	+++	Low	Low

Composition of the compost of the two full-scale organic waste treatment runs (22 days) and disintegration of test products in mesh bags were measured, and the final qualification of the disintegration rate of tested compostable products and their risk of ending up in discarded residue fractions or contaminating the final compost were evaluated.

According to the observations, after two waste treatment cycles of this trial, none of the investigated test products were likely to cause visual contamination (the risk of visual contamination of the compost is considered low because in case disintegrated fragments pass the 10-mm sieve, they will not be easily recognized as plastic contaminants) with plastic residues of the final compost. All selected compostable plastic products in this trial were not expected to contribute significantly to the residue to be discarded in the waste treatment process (operated at Valor) because of their recirculation procedure.

One cycle of primary compost production (11 days) was sufficient for complete disintegration of a PLA plant pot (see Table 1, product D). Disintegration of product D was significantly faster in comparison with disintegration of paper or other organic materials, including the reference products like orange peel and banana skin.

The disintegration rate is shown Table 1 and is more attributed to the type of material the product is made from than its thickness because thin compostable waste bags were not completely disintegrated within one cycle of 11 days (Van der Zee and Molenveld, 2020).

Conclusions

Food packaging waste takes a significant part of municipal solid and biowaste and it is rapidly growing, resulting in environmental concerns, and at the same time increasing the trend and demand for sustainable circle economy solutions. Biodegradable compostable packaging looks a promising way to reduce waste volumes and bring food packaging transformation from linear to circular economy. Food packaging industry already has options of compostable packaging that meets biodegradation and composting standards and does not impact environmental contamination. Synthetic polymers, such as PLA, are the most popular materials for packaging with high biocompatibility and biodegradability. Wider production of renewable biomass food packaging products (cellulose, starch) seems to be the next step and is most likely to make a firm growth in industrial food packaging applications. However, there is a need for further research to solve product shelf life, hygiene, safety issues and to evaluate overall environmental benefits and threats.

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