DOI: 10.15199/42.2023.2.2

WANDA SIKORSKA / ORCID: 0000-0002-5651-8859 / wsikorska@cmpw-pan.pl
JOANNA RYDZ / ORCID: 0000-0003-3972-7074 / jrydz@cmpw-pan.pl
ADRIAN DOMIŃSKI / ORCID: 0000-0002-7716-5597 / adominski@cmpw-pan.pl
MARTA MUSIOŁ / ORCID: 0000-0002-5776-578X / mmusiol@cmpw-pan.pl
GRAŻYNA ADAMUS / ORCID: 0000-0001-5439-7400 / gadamus@cmpw-pan.pl
MAREK KOWALCZUK / ORCID: 0000-0002-2877-7466 / mkowalczuk@cmpw-pan.pl
CENTRE OF POLYMER AND CARBON MATERIALS, POLISH ACADEMY OF SCIENCES, ZABRZE, POLAND
SIMONE MARANGHI / ORCID: 0000-0003-1295-6731 / s.maranghi@ecoinnovazione.it
LORENZO TOSTI / ORCID: 0000-0002-4659-9923 / l.tosti@ecoinnovazione.it
ECOINNOVAZIONE SRL, BOLOGNA, ITALY

DISPOSAL OF COMPOSTABLE PLASTIC PACKAGING MATERIALS UNDER CONTROLLED INDUSTRIAL CONDITIONS IN VIEW OF LIFE CYCLE ASSESSMENT

UTYLIZACJA NADAJĄCYCH SIĘ DO KOMPOSTOWANIA PLASTIKOWYCH MATERIAŁÓW OPAKOWANIOWYCH W KONTROLOWANYCH WARUNKACH PRZEMYSŁOWYCH Z PUNKTU WIDZENIA ANALIZY CYKLU ŻYCIA

ABSTRACT: Reducing the disposal of packaging waste and promoting a more circular economy are the current challenges of modern global economy. The Circular Economy Action Plan for a cleaner and more competitive Europe concerns the entire life cycle of products, from design and manufacturing to consumption, repair, reuse, recycling, and bringing resources back into the economy. Some plastic packaging items could be compostable under industrially controlled conditions in bio-waste treatment facilities. The article reviews and discusses previous studies on industrial composting carried out at the composting plant in Zabrze of selected biodegradable polymeric materials in terms of life cycle assessment (LCA).
Key words: waste management, recycling, (bio)degradable polymers, industrial composting, LCA

STRESZCZENIE: Ograniczenie ilości odpadów opakowaniowych i promowanie gospodarki o obiegu zamkniętym to aktualne wyzwania nowoczesnej gospodarki w Europie i na świecie. Plan działania dotyczący gospodarki o obiegu zamkniętym na rzecz czystszej i bardziej konkurencyjnej Europy dotyczy całego cyklu życia produktów, od projektowania i produkcji po konsumpcję, naprawę, ponowne użycie, recykling i ponowne wprowadzanie zasobów do gospodarki. Niektóre opakowania z tworzyw sztucznych mogą nadawać się do kompostowania w warunkach kontrolowanych przemysłowo w zakładach przetwarzania bioodpadów. W tym artykule dokonano przeglądu i omówiono wcześniejsze badania dotyczące kompostowania przemysłowego prowadzonego na kompostowni w Zabrzu wybranych biodegradowalnych materiałów polimerowych z punktu widzenia analizy cyklu życia (LCA).
Słowa kluczowe: gospodarka odpadami, recykling, polimery (bio)degradowalne, kompostowanie przemysłowe, LCA

INTRODUCTION

Every year around 2 billion tons of solid waste are produced in the world. According to experts' predictions, in just 30 years, we can expect the production of waste at the level of 3.4 billion tons per year. This drastic increase will pose a major challenge to waste management in the context of the entire planet. It is therefore worth thinking now about how we can reduce the production of waste as much as possible. The end-of-life options, used in waste management, include reuse, energy recovery (incineration) and recycling. The recycling is the intentional action that aims to reduce the amount of waste deposited in landfills by industrial apply of this waste to obtain raw materials or use of waste as a full-valuable materials for further processing (chemical or mechanical recycling). What's important, the recycling are recommended waste treatment option fit to the circular economy model. [1-3]

THE WASTE MANAGEMENT IN PRACTICE

According to the circular economy the existing resources should be rationally use, minimize waste and try to keep the using items in circulation as long as possible. It was the last of the postulates mentioned that was the inspiration for the creation of the Reuse Point in Zabrze. Such facilities have been operating in many countries for a long time, now also in Poland (Figure 1).

In this place everyday objects such as furniture, books or toys, which for some have already lost their value get a new life and in accordance with the principles of circular economy return to reuse in a new form.

Presently the "green", ecological production of chemical products and modern technologies, taking into account aspects related to the natural environment are widely implemented by different manufacturer of industrial chemicals, for example PCC Group Company. PCC Group offers a new chemical products in the PCC Greenline® segment, also manufactured from recycled raw materials and bear the "Production based on recycled materials" mark. An examples may be adhesives designed for bonding styrene-butadiene rubber (SBR) granulates obtained from the recycled car tires, as well as adhesives for rebond foam produced from ground mattresses.

FIGURE 1. REUSE POINT - BACK2LIVE, AT THE POINT OF SELECTIVE COLLECTION OF MUNICIPAL WASTE (PSZOK)

(FROM HTTPS://WWW.FCC-GROUP.EU/PL/POLSKA/AKTUALNOSCI.HTML)

However, technologies limiting the production of waste aimed at their processing and further use require specialized production processes, raw materials, additives and chemicals. [4] The use of renewable resources for the production of biodegradable polymeric materials and the production of goods based on them, combined with the process of their composting after fulfilling their intended utility functions, is a unique opportunity to adjust the life cycle of this type of materials to the natural cycle of matter. Such a life cycle cannot be achieved with conventional plastics. [2]

Taking into account the biowaste, the organic recycling (composting and anaerobic digestion) are used. The polymeric materials and the final products made of them are considered as susceptible to composting if they meet the EN 13432:2000 standard, i.e. they are biodegradable in at least 90% in less than 180 days [5]. Biodegradable packaging intended for composting should have a special mark and be collected together with organic waste. Organic biowaste generated in households should be separated from the municipal waste stream. The excellent solution in the case of home collecting organic waste are the compostable bags. Whereas, the selective collection systems implemented in many European countries are mainly based on special containers with appropriate colors (Figure 2). [6]

FIGURE 2. CONTAINERS FOR WASTE SEGREGATION

FIGURE 3. THE BASKET WITH TESTED SAMPLES AND COMPOST

THE ORGANIC RECYCLING

Packaging and packaging materials suitable for composting and treatment under anaerobic conditions show the ability to biodegradation and disintegration during test, and the products of this process do not have a negative impact on the quality of the obtained compost. The (bio)degradation of polyesters occurs as a result of the action of specific enzymes or by the hydrolysis of ester bonds, and most often both of these mechanisms occur in the appropriate sequence. Thus, the mechanism of the biodegradation process is complex, involving many chemical and biological reactions. The final products of this process are: biomass (organic matter), water and gases – carbon dioxide (CO_2) for aerobic, methane (CH_4) for anaerobic conditions. [7,8]

In the field of biodegradable materials, aliphatic polyesters currently produced on a commercial scale: polylactide (PLA) and polyhydroxyalkanoates (PHAs), as well as aliphatic-aromatic polyesters of the Ecoflex® type and their polymeric blends are of particular interest. The composting tests were also performed for final products in form of market bags as well composite items [9-12], Table 1.

TESTS UNDER INDUSTRIAL COMPOSTING CONDITIONS

At the Centre of Polymer and Carbon Materials, Polish Academy of Sciences (CMPW PAN) a systematic research under industrial composting conditions are conducted, based on developed methodology for polymeric materials. Samples tested were putted in racks at specially designed stainless steel baskets with dimensions of 27 x 70 x 21 cm (width x length x height, see Figure 3).

The baskets with samples were placed in the tested environment: in a compost pile, a KNEER system container or in one of the BIODEGMA system module at a depth of 0.5-1 m below the compost surface and incubated for a specified time are performed at the municipal waste disposal premise in Zabrze, Poland. [13-17]

In the studies the final products such as rigid films, food storage trays made of polylactide type PLA2002D and its polymeric blends with synthetic poly([*R,S*]-3-hydroxybutyrate) (aPHB), obtained by ring-opening polymerization (ROP) of β-butyrolactone (β-BL) were used. Whereas, the prototype cosmetic containers were produced by 3D printing from a commercial PLA/PHA filament from ColorFabb containing 12% PHA. [18,19] Research was also carried out for materials with a higher degree of processing. During the incubation of the samples, the characteristic parameters of the tested environments were monitored, and the current weather conditions were obtained from the Provincial Inspectorate for Environmental Protection. After appropriate incubation times (depending on the type of composting system), subsequent samples were withdrawn from the degradation environment. After each collection, the samples were cleaned in distilled water and then dried to constant mass at ambient temperature.

TABLE 1. LIST OF TESTED MATERIALS WITH REFERENCES

Type of polymer	Description of materials tested	Ref.
poly(*D,L*-lactide) (PDLLA)	PDLLA contain 12 mol% of *D*-lactide, a commercial product of GALACTIC Company, monofilament with thickness of 1 mm obtained using a laboratory single-screw extruder	
poly(*L*-lactide) (PLLA)	monofilament produced as described above	[24]
poly(1,4-butylene adipate-*co*-1,4-butylene terephthalate) (Ecoflex®, PBAT)	commercial product of BASF Company, monofilament produced as described above	
Ecoflex®	monofilament produced as described above	
PBAT, PDLLA	monofilament of blend PBAT/PDLLA (70/30) produced as described above	
PBAT, PDLLA	monofilament of blend PBAT/PDLLA (90/10) produced as described above	[25]
PBAT, PDLLA, synthetic analogue of natural poly([*R*]-3-hydroxybutyrate) (PHB) – poly([*R,S*]-3-hydroxy butyrate) (aPHB)	monofilament of blend PBAT/PDLLA/aPHB (90/5/5) produced as described above	
PDLLA, aPHB	multilayer packaging materials produce from paper and one layer of blend PDLLA/aPHB (90/10)	
PDLLA, aPHB, poly(vinyl alcohol) (PVA)	multilayer packaging materials produce from paper and two layers of PDLLA/aPHB (90/10) blend and PVA	
poly(ε-caprolactone) (Solvay, ε-PCL), aPHB	multilayer packaging materials produce from paper and one layer of blend ε-PCL/aPHB (90/10)	[26]
Solvay, aPHB, PVA	multilayer packaging materials produce from paper and two layers of ε-PCL/aPHB (90/10) blend and PVA	
PVA	multilayer packaging materials produce from paper and one layer of PVA	
polylactide (PLA), PBAT	commercial biodegradable bags (CONS-PET and Bio Planeta) contain polylactide (13 and 20%), and commercial additives	[16]
polylactide	commercial product (NatureWorks LLC, US, type 2002D, with 3.5% of *D*-mers content). was reprocessed 0, 1, 2 and 3-times in a co-rotating twin screw extruder	[23]
polylactide, aPHB	commercial product (NatureWorks LLC, US, type 2002D, with 3.5% of *D*-mers content) and blend with 15 mol% of synthetic aPHB, the samples were prepared in the form of rigid films with the average thickness of 0.3 mm on the test stand for extrusion of flat film	[20], [21]
polylactide	rigid packaging (trays) obtained from vacuum thermoformed films on a stand with a negative form	[22]
Ecovio® F Mulch C2311	blend of PBAT with 12 mol% PLA, a commercial product of BASF company, in the form of a dumbbell--shaped (thickness of 1.5 mm) or film with thickness of 80 µm as a prototype of the cosmetic packaging	[17]
polyethylene (PE) contained commercial totally degradable plastics additives (TDPA)	commercial shopping bag from a Polish supermarket labeled as an "ECO bag – bag that undergoes 100% biodegradation in 12 months"	[9]
ε-PCL type CAPA™ 6800 (Solvay)	composites of crosslinking ε-PCL with flax fibers	[11]
PLA, PBAT	blends of PBAT and PLA, containing 17 and 40 mol% of PLA in form of film (thickness of 0.02 mm), and 40 mol% of PLA in form of disposable bag type market, prepared by Bioerg Company (thickness of 0.1 mm), by means of the extrusion process on a test stand to extrusion of conventional flat film using a single-screw extruder	[10]
PLA, polyhydroxyalkanoate (PHA)	prototype of cosmetic containers in the form of jars obtained from commercial PLA and PLA/PHA blend 3D printing filaments using fused deposition modeling printer	[19]
polylactide	composites of polylactide type 2003D (Cargill Dow LLC, Minnetonka, MN, USA, with 4% of *D*-lactic acid) containing 0.5, 5 and 10 wt% of coffee, cocoa or cinnamon extracts	[12]
poly(3-hydroxybutyrate-*co*-4-hydroxybutyrate) (P3HB4HB, Sogreen00A)	P3HB4HB and its composites with cork in form of 1BA test specimen were prepared using the micro-extruder MiniLab	[13]

FIGURE 4. DIGITAL PHOTOGRAPHS OF THE THERMOFORMED FINAL PRODUCT FROM PLA RIGID FILM BEFORE AND AFTER 1, 2 AND 3 WEEKS OF DEGRADATION IN A KNEER SYSTEM CONTAINER

The degradation progress of the tested polymeric materials was followed by determining changes in their average molar masses and dispersion with use gel permeation chromatography method (GPC). In addition, composition and thermal properties were also monitored, as well as macroscopic and microscopic changes in the surface of the samples were observed (Figure 4).

Results on the biodegradation process are presented in a series of publications. [13-27] The incubation process of the multi-reprocessing materials was carried out in a composting pile at an average temperature of 61 ºC and an average pH of 7.0. The impact of processing (as the recycling model) on the disintegration of the tested samples was found. The disintegration of materials with a higher degree of processing, above 3 cycles of passage through the extruder, was found already in the first week of incubation in the composting pile. The samples processed 1, 2 and 3 times, disintegrated only after 6 weeks of incubation, which was not found after 3 weeks of this process (Figure 5). [23]

In recent years, the biodegradable packaging industry has seen an increase in interest in the use of composites of biodegradable polymers with natural fibers that meet the directions of activities in accordance with the principle of sustainable development. The challenges related to the design of polymer biocomposites that are stable during use, as well as susceptible to attack by microorganisms during organic recycling, are still current. The current research focuses on the application of the developed research methodology to assess the impact of the content of fillers in composites and other additives on the composting process of the polymer matrix. [12,13]

The obtained results indicated that in selected environment of industrial composting the hydrolytic degradation via random ester bond scission, like to it occur under abiotic conditions, is preferentially. However, the observed progressive decrease in pH of sterile extract (SE) of industrial compost at invariable pH of the nonsterile extract (NSE) indicates that microbes present in compost can assimilate the products of abiotic hydrolysis of the incubated samples [20]. Moreover, the differences observed in the degradation rate of final products (bags) of Bioerg Company with a similar content of the PLA component could be suggest the influence of materials thickness or the commercial additives used during processing on degradation profile under industrial composting condition. For example the presence of talc may interfere with materials behavior towards water and consequently the course of biodegradation changes [10].

Studies of the industrial composting process were also carried out for an oxo-degradable bags offered previously in markets. It was found that their disintegration occur longer than 6 months, therefore these materials should not be labeled as compostable. The slow degradation and fragmentation is probably due of partially crosslinking after long time of

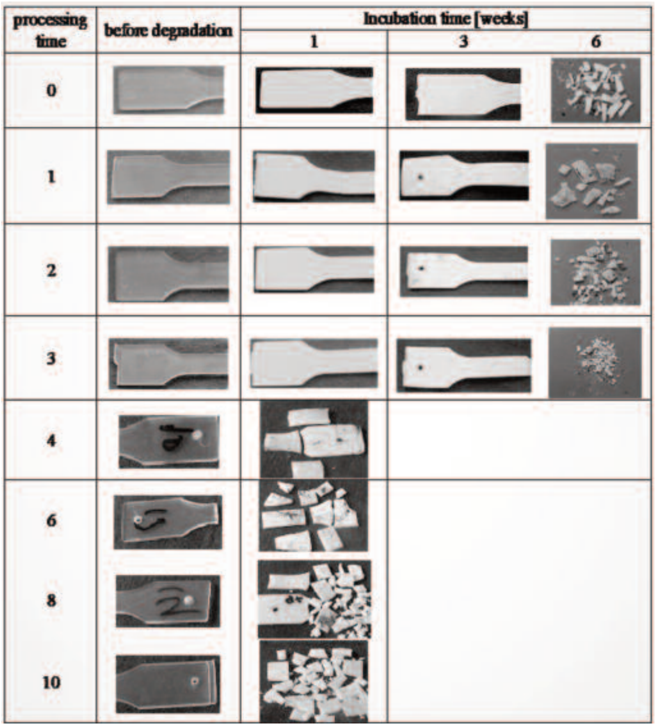

FIGURE 5. DIGITAL IMAGES OF THE PROCESSING SAMPLES BEFORE AND AFTER INCUBATION

degradation, which results in the limitation of low molar mass residues for assimilation [9].

INDUSTRIAL COMPOSTING IN TERMS OF LCA

Compostable plastic materials are still in the early stages of development and occupy a small market niche. Their further development is related to the improvement of properties, availability and lowering the price, as well share the municipal organic waste collection systems [28]. In order to assess the environmental impact of the composting process, the life cycle assessment (LCA) methodology can be applied to the municipal waste stream generated. According to the ISO 14040 standard, the life cycle is defined as "successive and interrelated stages of a product, from obtaining or producing a raw material from natural resources to its final disposal". The application of LCA is carried out through a step-by-step procedure, and it involves four main phases: i) goal and scope definition, ii) life cycle inventory (LCI), iii) life cycle impact assessment (LCIA), and iv) interpretation and improvement [29, 30]. The LCI phase is one of the most critical phases since it deals with data collection to map all the input and output flows (i.e., material and energy consumptions, emissions, waste) characterizing the system under study. The application of LCA allows for the evaluation of the environmental impact of the investigated system, suggesting which could be the actions to reduce environmental burdens and support the municipal waste eco-balance. In this sense, renewable raw materials could be a more favorable solution to employ instead of non-renewable ones. Taking biomaterials as an example, they could be a viable option to replace conventional fossil-based materials, enabling the reduction of CO_2 emissions, because plants absorb CO_2 from the air in the photosynthesis process. The application of LCA allows for an overall evaluation of the several factors that may potentially affect the environment and are related to the municipal waste management process, in this case, organic recycling. In this regard, applying LCA to industrial composting based on the phases reported in ISO standards should define several important parameters. One of these is a functional unit (i.e., the unit of measure to which all the impact calculation shall be referred). A potential functional unit for composting can be, for example, the amount of household waste generated in a geographically defined area taking into account specific local conditions. Data used may come from direct measurement, research, experiments, and literature. For the LCI of compostable municipal waste, and thus for the assessment of its impact on the environment, the accounting of inputs and outputs of the composting process (i.e., biological treatment), must be carried out. The biological treatment of organic compounds and paper leads to biogasification, with the production of gases (mainly CO_2, CH4 and steam) and biomass (compost in an aerobic process). Biological treatment processes contribute to the stabilization of waste destined for landfill, as well as valorization in the context of biogas and compost production. The inputs may include non-segregated municipal waste, segregated bio-waste, residues mechanically separated in the fuel production process alternative, as well as energy consumption. Main outputs may include inert waste for landfill, recovered raw materials, compost, and environmental emissions. The amount of energy consumption could be assumed as 30 kWh/t of waste as input to the composting plant (50% compost production, the remaining 50% was lost to evaporation and emissions).

These data and information are an excerpt of the data needed to calculate the environmental impact of industrial composting. [31]

CONCLUSION

The results presented in this review indicate that the methodology used for testing of biodegradable packaging materials, developed in Zabrze, enables the disposal of plastic packaging wastes under industrial composting condition in a way that is friendly and safely to the natural environment and residents. However, the increasing demand for biodegradable plastics creates new opportunities, but also challenges. Thus, the European Commission introduced a proposal for a Regulation on Packaging and Packaging Waste (PPWR) which will repeal the existing Packaging and Packaging Waste Directive (PPWD) and harmonize the packaging waste regime across the EU. The Article 8 defines conditions for packaging to be considered compostable and stipulates that tea bags, filter coffee pods and pads, sticky labels attached to fruit and vegetables and very lightweight plastic carrier bags (wall thickness below 15 microns) shall be compostable by 24 months after the entry into force of the Regulation. The provision further empowers the Commission to adopt delegated acts to amend the list of packaging that need to be compostable. [32] Therefore, it is extremely important that the design of such polymers should be carried out in a responsible and sustainable manner, and the operational and design activities must be carried out taking into account aspects related to exploring the natural environment.

It may be therefore concluded, that the biodegradable packaging susceptible to organic recycling (composting under industrial conditions) seem to be a perspective panacea for decreasing of landfill waste.

ACKNOWLEDGEMENTS: This work was supported by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 872152, project GREEN-MAP and an international project co-financed by the program of the Minister of Science and Higher Education entitled "PMW" in the years 2020-2023; contract No. 5092/H2020/2020/2.

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The authors deeply acknowledge FCC Śląsk Sp. z o.o. – Silesian Recycling Park – Mechanical and Biological Waste Processing Plant in Zabrze (https://www.fcc-group.eu/pl/polska/oddzialy-spolki/mpgk-zabrze.html), dealing with selective collection and processing of waste, for providing the research sites for conducting industrial composting tests.

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