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ORIGINAL PAPER

Product Ecodesign: An Application of Bio-Based Materials in the Personal Care Packaging Industry

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Abstract
The increasing amount of plastic materials produced and their persistence in the natural environment after the use stage makes them highly critical from the environmental viewpoint and human health and much efforts are being made to find valid alternatives worldwide. This is particularly true for the packaging industry where the use of plastics is more intense and products often have a very short useful life. Ecodesign is a recognized approach capable of proposing effective solutions to reduce the impact of plastic materials, including their replacement with alternative ones. In this view, bioplastics have been recognized as a new generation of materials characterized by a potential lower environmental burden, along their life cycle, including the end-of-life phase. The same cannot yet be said for their technological and production performance, both at an industrial level and the use phase, especially for durable products.
This article refers to the personal care industry and aims at exploring, in the Circular Economy framework, the Ecodesign of a personal care plastic dispenser. In this specific sector, the use of bio-based materials is still very limited and in an early stage, differently, from other industries (e.g. agri-food) where, instead, the applications are much more widespread. In particular, a *material substitution* solution drew on bio-based materials has been adopted in respect of conventional polypropylene and polyethylene. The technological performances of such bio-based materials have been evaluated through laboratory, production and use tests; the results obtained highlight that they are reaching levels comparable to conventional plastics. The regulatory, environmental and economic implications of their potential use at an industrial level are also discussed.

Keywords Circular Economy · Ecodesign · Plastic Packaging · Material Substitution · Bioplastics · Personal care industry

Introduction

Evolutionary trends show that in the second half of the twentieth century the environmental burden associated with industrial products was constantly growing. It depends on market factors (number of products on the market and reduction in their useful life), on their intrinsic

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characteristics (structural complexity and weight) and on design solutions often aimed at reducing costs and production times. The potential joint effects on the availability of some materials and on the impacts during the production and end-of-life phases of these products have stimulated, both at a scientific and regulatory level, the promotion of new strategies, approaches and solutions for reducing the overall impact they generated on their life cycle [1]. Many of these solutions leverage the design phase—through the s.c. Ecodesign—which is recognized as having a key role in determining the environmental performances of a product [2–5].

Some products and materials have been affected more than others by the need for "transition" towards more sustainable ones. In this perspective, a prominent place has certainly been given to the use of plastic materials in the packaging industry, especially for mono-material products with a simple structure and relatively short useful life, where most of the initiatives have been aimed at containing the effects associated with the use of plastics in single-use products and in secondary packaging (i. e., shopping bags, food packaging, food service packaging, etc.) [3, 5, 6]. However, in the world of plastic packaging there are products that have a more complex structure and provide usage functions for a longer life period. For these products there is still a significant gap with respect to how their environmental sustainability can be improved without compromising their manufacturability and their performances in the use phase. This is the case of rigid packaging and, in particular, of plastic dispensers. Implementing an Ecodesign strategy on this type of products, intended for industrial customers (final producers of the bulk contained in them) who require maintaining unchanged their technical standards, prices and performances, is even more complex [7].

The study presented describes the experience gained in the implementation of an Ecodesign strategy focused on the *material substition*—use of bioplastics instead of conventional ones—applied to a rigid plastic dispenser used in the personal care industry.The field of analysis strengthens the novelty of the study, considering that, at present, the scientific literature shows that major applications of bioplastics in packaging mainlyconcern flexible packaging and the agro-food industry [8, 9].

The current manufacturing and use performances of these materials and the overall potential expressed in terms of replacement of conventional materials have been investigated. The research has been performed through a series of functional and use tests conducted in collaboration with a leading company of the packaging industry ("the producer" hereafter).

The article is structured as follows: Section 2 describes the theoretical-methodological background -Ecodesign- and the technological and regulatory context -use of plastics and bioplastics in the packaging industry- to which the study refers. Section"Materials and Methods" describes the technical and production characteristics of the product under study, the selection criteria for materials replacement and the test protocol and indicators envisaged. Sections"Results" and 5 respectively illustrate and discuss the results obtained, while in Section 6 the conclusions of the study are drawn, highlighting its limitations and prospective developments.

Background of the Study

Products and Packaging Products Ecodesign

Ecodesign, defined as the integration of environmental aspects into product development, has emerged in the 1990s with the aim of reducing environmental impacts throughout the product life cycle [10]. Compared to conventional industrial design, in Ecodesign environmental requirements are considered already in the early stages of a product's development, together with more traditional industrial values, such as profit, functionality, aesthetics, ergonomics, image and the general quality; in the same way, during its design, all the phases of the life cycle must be considered, i.e. all the activities to extract the raw materials, to distribute the product, to use it and finally to dispose of it [3].

The main Ecodesign strategies are the following [11, 12]:

a) minimize resources—reduce the use of materials and energy;
b) choose resources and processes with low environmental impact—select the most "eco-friendly" materials, processes and energy sources;
c) optimize the life of products—design artefacts that last over time and are used intensively;
d) extend the life of materials—design based on the valorization of disused materials through recycling, composting or energy recovery;
e) facilitate disassembly—design according to the separation of parts and/or materials.

In this regard, implementing Ecodesign principles is considered a strategic key to success to achieve Circular Economy aims [13].

As mentioned, one of the most promising strategies in the adoption of Ecodesign principles concerns the use of materials with a low environmental impact [14–16]. When thinking about replacing a material with another that generates less impact it is possible to take into consideration some principles such as eco-efficiency, non-toxicity, renewable sources and short distribution chain [17]. Moreover, several factors have to be considered also during the material selection, where the designers play an active role, because their choice has to be closely connected to the client and production requirements [18, 19]. This is even more true concerning conventional plastic materials due to their large use in a wide range of applications and to their well-known environmental implications [20].

Packaging is a field where numerous applications of Ecodesign can be found; most of them are focused on reducing weight, volume and, therefore, costs and impacts of transportation and storage of products; enabling reuse or recovery, including recycling; minimizing the presence of toxic substances and materials and other hazardous substances [5, 12, 21, 22]. In particular, for secondary packaging efforts are also directed to make them as reusable as possible, while for primary packaging to optimize the end-of-life stage [10, 23, 24].

Plastics Packaging: Environmental Issues

Plastics are one of the most widely used packaging materials, popular because of their flexibility, lightweight, ease of processing and low cost. Beyond these positive characteristics that have allowed a wide diffusion in the last seventy years, plastics have many criticalities from an environmental point of view, especially due their persistence on natural environments and their composition, as the 99% of the raw materials for plastic production are non-renewable ones, and only 1% of global plastic production is from renewable raw materials [25]. This has meant that, in recent years, they have received an increasing attention from the international community, intent on drastically reducing their use and progressively moving towards their replacement [14].

The personal care and beauty industry industry is recognized as one of the major contributor to the global plastic waste crisis [26]; this is mainly related to the large production (and the subsequent disposing of) of dispensing products that it is estimated reaches over 120 billion packaging units every year [27].

To prevent and reduce the impact of plastics on the environment, the European Commission is proposing actions aimed at rethinking and improving all the value chain, promoting reuse and recycling solutions and calls for a transition towards bio-based, biodegradable and compostable materials. In particular, in January 2018, the European Union (EU) adopted the European Strategy for Plastics [28], as part of the EU's Circular Economy Action Plan, buildings on existing measures to reduce plastic waste. The strategy identifies key challenges, including the low reuse and recycling rates of plastic waste, the greenhouse gas emissions associated with plastics production and incineration, and the presence of plastic waste in oceans. The Commission proposes that all plastic packaging should be designed to be recyclable or reusable by 2030. Later in the 2019, the European Directive on single-use plastics enters into force with the aim to seriously target the issue of plastic marine litter [29] and in 2022, the European Commission adopts the Communication providing the policy framework for bio-based, biodegradable and compostable materials, also including proposals to improve the packaging design [30].

Altought the efforts of the European legislator, on the one hand, and companies, on the other, to mitigate the environmental impacts of their packaging, plastic waste from packaging still remains a big issue [31–34]. To efficiently face this pressing problem and contribute to a sustainable plastics economy, an active collaboration throughout the packaging value chain, from material developers and manufacturers to packaging suppliers, brand owners, retailers, consumers and recyclers, becomes vital for driving the sustainability goal and searching for continuously innovative product solutions [35, 36].

Bioplastics and Packaging Products

The concept of "bioplastics" includes a broad range of materials and products that are bio-based, biodegradable/compostable or both (Fig. 1). Bio-based means a material or product that is derived from biomass whereas biodegradable/compostable identifies materials which can be transformed by a natural chemical process into natural substances such as water, carbon and biomass with the help of microorganisms [33]. The process of biodegradation depends on the surrounding environmental conditions (e.g. location or temperature), on the material and on the application.

The family of bioplastics is divided into three main groups [37]:

1. *bio-based or partly bio-based, non-biodegradable plastics* such as bio-based polyethylene (PE), polypropylene (PP), or polyethylene terephthalate (PET) (so-called drop-ins) and bio-based technical performance polymers such as polytrimethylene terephthalate (PTT) or thermoplastic copolyester elastomers TPC-ET);
2. *plastics that are both bio-based and biodegradable*, such as polyactalacid (PLA) and polyhydroxyalkanoates (PHA) or polybutylene succinate (PBTS). This group includes starch blends made of thermo-plastically modified starch and other biodegradable polymers;
3. *plastics that are based on fossil resources and are biodegradable*, such as polybutylene adipate terephthalate (PBAT).

At present, bioplastics represent less than 1% of the more than 390 million tonnes of plastic produced annually [38]. In 2022, the global bioplastics production capacity

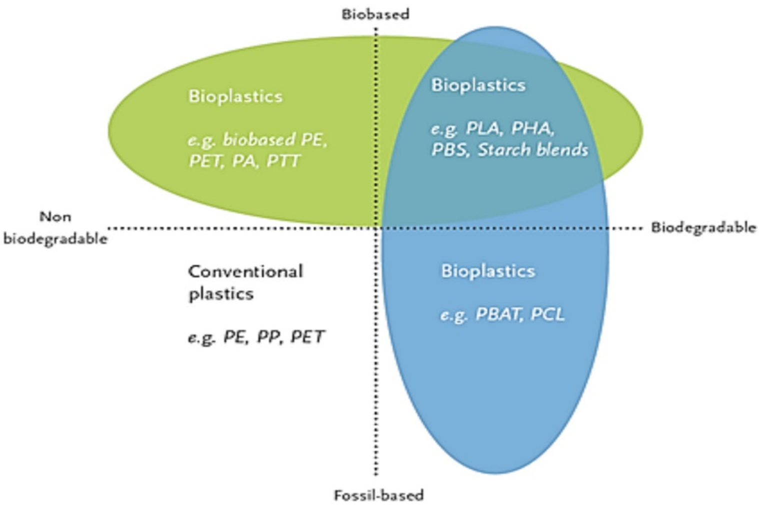


Fig. 1 Material coordinate system of bioplastics. Source: European Bioplastics, 2022a [38]

amounted to around 2.2 million tons. However, demand is rising, with more and more sophisticated bioplastic materials and products entering the market. By 2027, the production capacity is expected to increase approximately to 6.3 million tons (Fig. 2), with most of these new volumes being converted to innovative packaging solutions [39].

The figure shows the potential global production capacity of bioplastics in 2027.

With an increasing number of available materials, applications and products, the number of producers, processors and end users of bioplastics is steadily increasing and significant progresses have been made in the view of: i) advanced technical and functional properties of such materials; ii) potential cost reduction through economies of scale; iii) new and efficient possibilities for managing their end-of-life; iv) consumer awareness of the environmental problems associated with traditional plastics; v) increase in oil prices [40].

Today, there is still no common agreement that defines a minimum percentage of biological mass that must be contained in a plastic material in order to be defined as "bioplastic". The use of standards, especially in the design phase of a product containing bioplastics is crucial. In this regard, the European Commission has created a commission within the European Committee for Standardization (CEN) aimed at harmonizing the various existing standards, among which: i) the European standard "CEN/TS 16137:2011 Plastics—Determination of biobased carbon content" (or ASTM D6866 standard) of the European Committee for Standardization (CEN), specifies the calculation method for determining the carbon content coming from renewable sources in plastic materials [41]; ii) the European standards EN 13432 on packaging (2000) [42] and EN 14995 on plastic materials (2003) [43] define the technical specifications for the compostability of products. If bioplastics are effectively compostable according to this standard, they can be treated in industrial composting plants [7].

Use of Bioplastics in the Packaging Industry

Packaging from bio-based plastics has developed over the past 20 years. New materials such as PLA, PHA, cellulose or starch-based materials are able to produce packaging

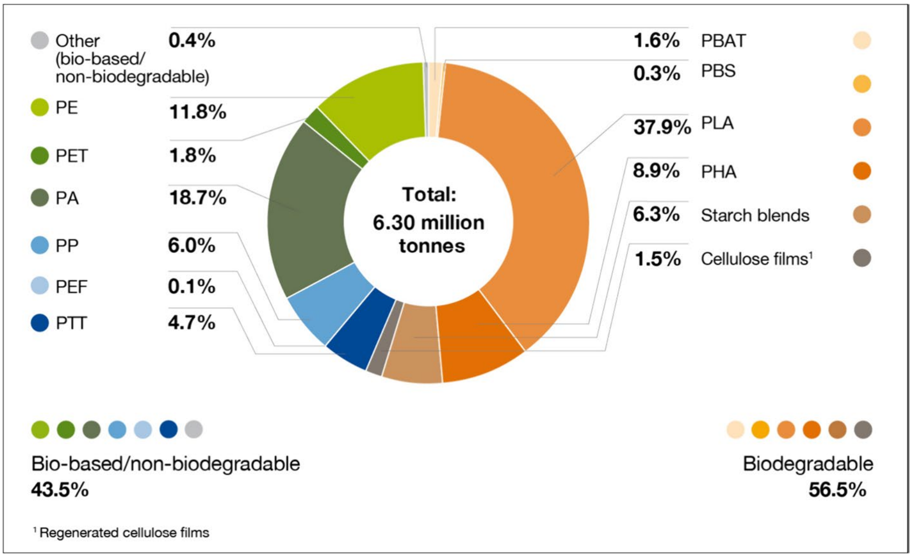


Fig. 2 Global production capacities of bioplastics in 2027 [39]

solutions with completely new functionalities, such as biodegradability or compostability. Packaging made from bioplastics can be processed with all customary plastics processing technologies, no special machinery is required. Depending on the type of bioplastics used, only the processing parameters have to be adjusted. A wide range of products suitable for numerous and varied applications has been developed within a short period, and nowadays, the quality of bioplastics packaging can easily match that of traditional products [39]. Bioplastics packaging solutions can be identified as concerning [37]:

Flexible packaging: many different bioplastics are used for flexible packaging solutions. Biodegradability is a feature often sought when it comes to food packaging products for perishables. Biodegradable food packaging certified as industrially compostable was the first successfully commercialized bioplastic product. Films and trays are particularly suitable for fresh products such as fruit and vegetables as they enable longer shelf life. In addition, confectionary, such as chocolate and biscuits, or dry food, such as tea or muesli, are now increasingly packaged with bioplastics.

Service packaging: food service packaging is another large growing segment. Whether it is cups, plates, cutlery or carrier bags, the entire product spectrum can be made from bioplastics. These products are especially used at sports events, street festivals, on planes or on trains. They can be made of bio-based non-biodegradable plastics or of bio-based biodegradable plastics, depending on the end-of-life solution envisaged for the individual product.

Rigid packaging: rigid bioplastics applications available for cosmetics packaging of compact powders, creams and lipsticks, as well as beverage bottles. Materials such as PLA, bio-based PE, or bio-based PET are used in this category. The high percentage of bio-based material in these products and the ability to combine them with those recycleds from conventional PE and PET has resulted in a significant increase of resource efficiency and a reduction of CO_2 emissions.

The biodegradability of certain types of bioplastics enables the joint recovery with food residue via composting or anaerobic digestion, provided that conventional plastics do not contaminate this recycling stream.

Materials and Methods

Methodological Approach

The product under study is a personal care plastic dispenser; it refers to a product that, assembled with a bottle, represents the primary container for the conservation and dispensing of fluid -bulk- substances. The Ecodesign principles [44, 45] that inspired the solution applied can be summarized in the following:

i) selection of materials based on required technical and environmental performances;
ii) the selected material must not affect production standards;
iii) product performances, during the use, must be manteined.

It must be considered that plastic dispensers present structural and functional characteristics that make some of the most widely practiced Ecodesign solutions in the sector, e.g. design for recycling, much more complex, due to the technical problems and costs associated with the separation of the materials it is made of, generally being handled together with the bottle in current public waste-treatment plants. The solution of replacing conventional plastics with bio-based ones is expected to reduce, in addition to the environmental burden associated with the use and processing of oil, also that connected to a more efficient end-of-life stage.

The study started from the investigation of the technical features and properties of bioplastics and the comparison with those of conventional plastics (based on safety and technical data sheets). After this initial step, the bioplastic materials have been subjected to laboratory, process and use tests in order to compare their quality and features with those of conventional plastics used by the producer. The laboratory tests were supposed to validate the basic characteristics of the material (as supplied by the supplier); the process tests to understand its workability characteristics on the production processes; the functional tests to simulate their performances during use by the consumer. The results obtained do not include what is currently considered as confidential information for industrial and commercial reasons. Figure 3 illustrates the product-system phases included in the Ecodesign solution proposed and the related tests conducted.

The figure highlights the main product life cycle stages involved in the study and the related tests reference areas.

Packaging Product Involved: State of the Art

The dispenser under investigation is made of four different plastic materials: Polypropylene (PP), Low Density Polyethylene (PE-LD), Linear Low Density Polyethylene (PE-LLD), Polyoxymethylene (POM) and Stainless Steel (Fig. 4).

The figure shows the specific components of the Dispenser interested by the use of bioplastics.

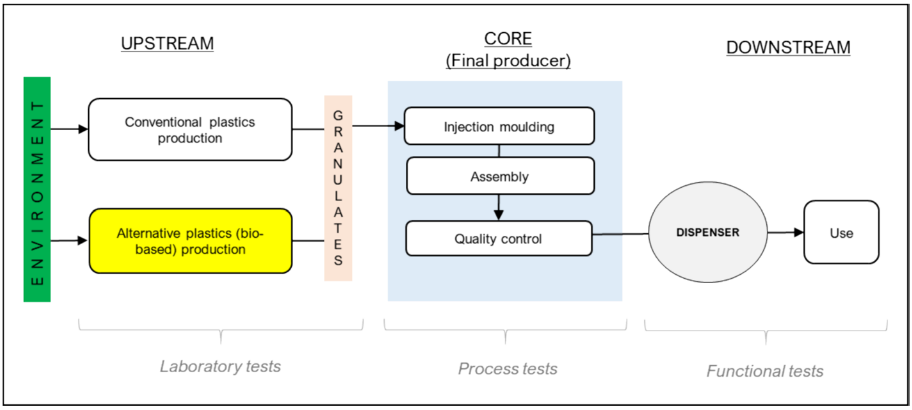


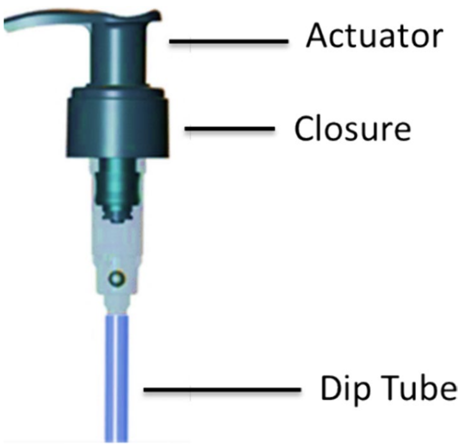
Fig. 3 The product-system considered in the Ecodesign solution promoted

Closure and actuator are currently produced by injection molding process using hydraulic presses, while the dip tube is produced by extrusion process. The basic injection molding process consists of the following steps:

– the plastic is introduced into the injection press in the form of granules, passing from the hopper into a heated steel cylinder which contains the screw that conveys the material into the injection chamber;
– the injection press thus heats the plastic until it reaches the liquid state;
– through the nozzle of the press the molten plastic is injected into the mold cavity;
– the material is then cooled until it forms a solid product;
– finally, the extractors will push the cooled product out of the press as a finished piece.

The pieces obtained require, in some cases, additional operations such as the removal of the material from the injection connections (the so-called “sprues”).

Fig. 4 The plastic dispenser analyzed



A streamlined life cycle environmental impact study was previously conducted on the original product in accordance with the ISO 14040 and ISO 14044 standards, which served as the baseline for the analysis in question. The study had the following characteristics:

- functional unit and reference flow: the functional unit is identified by the number of dispensings considering a dosage of 2.00 cc and 300 ml of soap. The reference flow based on the single dispenser.
- system boundaries: the study considers the following activities: extraction of raw materials, production of components (moulding, extrusion and vulcanisation), assembly and transport.
- allocation procedure: the data was allocated following the "mass principle".

Data collection was conducted including major suppliers and approximately 90% of the total product mass is based on on-site data collection. In particular, as regards the Global Warming Potential indicator (GWP100) expressed in kg of CO_2 equivalent, the analysis revealed that during the life cycle of the dispenser, almost 65% of CO_2 emissions derive from the extraction of raw materials; 30% comes from the use of energy; 5% from transport. Also for that reasons it was considered that the material substitution solution was the most suitable to obtain significant results in acceptable times and above all configured an alternative scenario that could be managed within the company.

More in detail, the potential replacement of oil-based plastics concerns the closure (PP), the actuator (PP) and the dip tube (HDPE) (Fig. 4) having that:

- those components represent more than 50% of the total weight of a dispenser;
- the internal module (engine) of the dispenser is composed of sensitive parts requiring additional mechanical and technical features;
- PP and PE are the conventional plastics for which there are more corresponding bio-based options.

To be validated for mass production, the dispenser must respect some assembly (i.e. retention force; screwing torque value) quality (i.e. vacuum sealing; dispensing load; breaking load) and functionality features (i.e., dosage; priming shots; storage temperature).

Bioplastics Under Investigation

Different typologies of bioplastics have been investigated, considering the technical features and properties of the conventional plastics adopted by the company for the same products. Potential bioplastics suppliers have been formally contacted by e-mail providing the data sheet of the conventional plastics (PP and PE) used by the producer for the production of the dispenser. Thus, an accurate screening has been conducted in order to identify alternative materials to be subjected to the qualification tests. More specifically, the following bioplastics (determined according to ASTM D6866, 2022), have been selected:

1. Bio HDPE 1 for substitution of closure and actuator material;
2. Bio HDPE 2 for substitution of closure and actuator material;
3. Blend of Bio LDPE (15%) and Bio HDPE (85%), for substitution of closure and actuator material;
4. Blend of Bio LDPE (20%) and Bio LLDPE (80%), for substitution of dip tube material.

According to the ASTM D6866 standard (2022), the minimum bio-based content of the resins above mentioned is considered in a range from 94 to 95%. As regards the features and properties of these bioplastics, the technical datasheet released by resins suppliers confirmed a good similarity with standard oil-based plastics, such as PP, in terms of control properties (e.g., melt flow rate and density). Bio HDPE 1 and bio HDPE 2 have both 94% bio-based content, but they present some differences in terms of technical characteristics; in particular, the melt flow rate of bio HDPE1 is higher than melt flow rate of bio HDPE2.

Other regulatory references taken into consideration in the selection of the replacement material were the following:

- *Regulation (EC) n. 1907/2006* of the European Parliament and of the Council, concerning the registration, evaluation, authorization and restriction of chemical substances ("REACH"). Each resin supplier is required to communicate the presence of dangerous substances if present in quantities greater than 0.1% [46].
- *Californian Proposition 65*, also known as the California Safe Drinking Water and Toxic Enforcement Act, which requires businesses to report if any of the nearly 900 listed chemicals and substances are present in the material [47].
- *Directive 94/62/EC* of the European Parliament and of the Council of 20 December 1994 on packaging and packaging waste [48].
- *Coalition of Northeastern Governors* (CONEG), which limits the use of heavy metals in packaging [49].
- *Regulation (EU) no. 10/2011* of the Commission (14 January 2011) concerning plastic materials and objects intended to come into contact with food products [50].
- *Regulation (EU) 2022/1616*, which repeals Regulation (EC) 282/2008 relating to recycled plastic materials and objects intended to come in contact with food products [51].
- *Regulation (EC) n.1223/2009* of the European Parliament and of the Council (November 30 2009) on cosmetic products [52].

Tests Conducted

The above-mentioned bioplastics typologies have been tested through a validation protocol, which was built including a set of tests commonly used in the packaging industry for the qualification of new materials, after described (all tests were carried out by comparing standard oil-based plastic and bioplastics) (Table 1):

Results

Laboratoy Tests Results

The results obtained from the laboratory tests conducted are the following:

- *Environmental stress cracking (ESC) on rectangular specimen*: the behavior of the standard PP during the cracking test was better than the bio-resins. However, the results obtained using the Bio HDPE were satisfactory and higher than expected (Fig. 5).

The figure shows the results of the Environmental stress cracking on rectangular specimen

Table 1 Description of the tests conducted

LABORATORY TESTS The laboratory tests were conducted on two types of specimens (rectangular and dog bone)	
NAME	DESCRIPTION
Tensile module test	The tensile module test has the purpose of testing some mechanical properties of a material, i.e. testing the resistance it has towards the stresses acting on it. The tensile test is a static test that provides quantities used in the design phase and in the evaluation of the applicability of technological processes to a material. For the test in Europe the reference standard is EN 10002. The instrument used is the Lloyd Dynamometer. The tensile test is performed on bone specimens with a thickness of 1 mm, through the application of an increasing uniaxial load
Tensile impact test	The "Tensile impact test", also called resilience test or Charpy test, is a dynamic test which consists of breaking a specimen of the material under examination with a single blow. This test measures the energy needed to break the specimen. As for the tensile test, "double T" specimens were also used for this test, exactly 10 specimens with a thickness of 1 mm and 10 specimens with a thickness of 1.5 mm were tested for each material. The instrument used is the S.C. Charpy pendulum
Melt Flow Index	The Melt Flow Index (MFI) is the quantity, expressed in grams, of molten plastic material that comes out of a capillary under the pressure of a certain weight and at a certain temperature. the MFI is linked to viscosity which, instead, expresses the resistance that a fluid opposes to flow. The equipment that was used to carry out the test includes an Extrusion Plastometer and a scale
PROCESS TESTS	
NAME	DESCRIPTION
Molding Test	The basic injection molding process was conducted as described in Sect. "Packaging product involved: state of the art". The alternative resins and standard PP were printed in four different colors in order to then also analyze the color rendering on the different types of plastic
Dimensional tests	Once the components of the dispensers were printed, third-party suppliers were asked to carry out a dimensional analysis of the component, i.e. a FAI (First Article Inspection). This inspection is carried out following the references provided by the individual control plans of each component
Assembly test	It is a test carried out to check that during the assembly phase the components do not break and that they are therefore able to resist the pressures and forces implemented by the assembly machine
FUNCTIONAL TESTS	
NAME	DESCRIPTION
Regulator retention test	It is a test that allows to measure the strenght necessary to separate the regulator from the stem. The instrument used is the dynamometer, which is capable of applying an increasing strenght on the sample until the two components separate. After fixing the component, the tensile test is carried out at a speed of 250 mm/min, until the two components separate. The machine records the maximum force, in Newton, needed to separate the two components
Ring retention test	It measures the maximum strenght necessary to separate the ring from the body (carried out in a similar way to the regulator retention test)
Aesthetic analysis	It is a visual check carried out on the assembled dispensers, following the guidelines of the control plan. This analysis also includes general aspects such as: lack of material; presence of oil/grease dirt; foreign bodies; stains in the material. Furthermore, with the help of the projector, it is checked whether the dimensions of the molding flashes are acceptable or not
Sun resistance test	Consisting of 24 h of exposition to a UV light at 1 mt of distance

- *Tensile module on dog bone specimens*: the results for the standard PP are 263 N for the F Max (maximum cracking specimens force) and 10.29 mm for the X Max (maximum specimens elongation). During the comparison test the closest results to the standard PP were obtained using the resin Bio HDPE 1 (F Max = 196 N – X Max = 9.32 mm) (Fig. 6).

The figure shows the tensile module results obtained

- *Impact strength on dog bone specimen*, applying the same load (N), as applied for the standard resin, the bio materials have shown a more critical deformation. However, no cracking was detected (Fig. 7 a-b).

The figure shows the deformation rate for bio materials on dog bone specimen

- *Melt flow rate (MFR) index* has been measured in order to confirm the parameter reported in the technical data sheet provided by the bio-resins suppliers; the results obtained confirmed those values (Fig. 8).

The figure shows the results of the Melt flow rate index.

Process Test

The results obtained from the process tests conducted are the following:

- *Molding test* of components has been performed to complete the "First Article Inspection (FAI)": during the molding phase; no significant issues were detected.

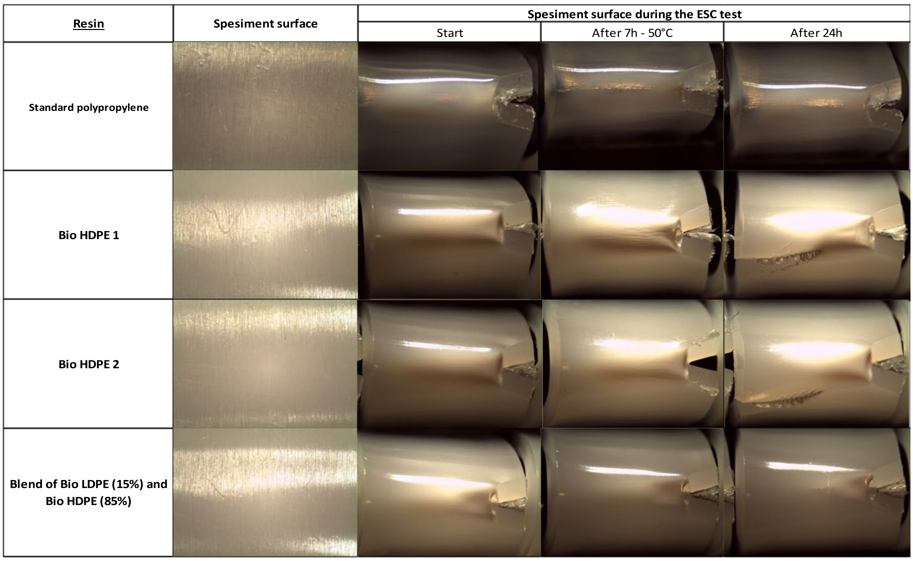


Fig. 5 Environmental stress cracking (ESC) results on rectangular specimen

Resin	F. Max Avg. (N)	X Max Avg.(mm)	Spesimen before and after the test
Standard polypropylene	263	10,29	
Bio HDPE 1	196	9,32	
Bio HDPE 2	221	17,21	
Blend of Bio LDPE (15%) and Bio HDPE (85%)	157	19,77	

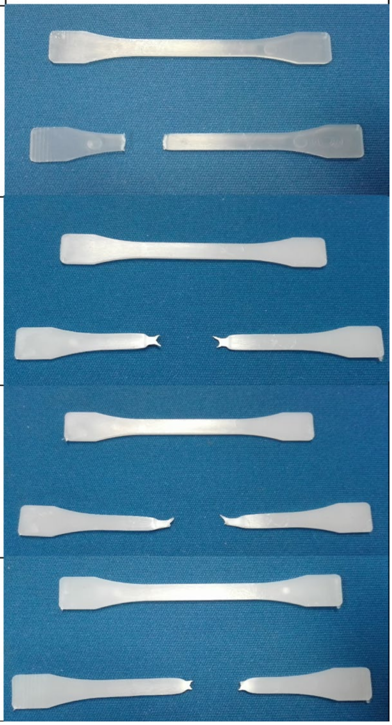


Fig. 6 Tensile module results on dog bone specimens

- The *dimensional analysis* showed, on bio molded components, a slightly out of specification still acceptable. This is due to the behavior of the bio PE, which allows a more severe shrinkage
- The *assembling test* with the use of high-speed machine has been performed without significant interruption.

Functional Test

The results obtained from the functional tests conducted are the following:

- *Regulator and ring retention test:* the results obtained did not show significant differences between conventional plastics and bioplastics.
- *Aesthetic analysis*: the results obtained from analysis of bioplastics products conducted by internal experts did not highlight particular differences about the aesthetic properties compared to the standard oil-based plastics as PP used for the finished components (Fig. 9).

The figure shows the aesthetic properties of conventional plastics compered to bioplastics products.

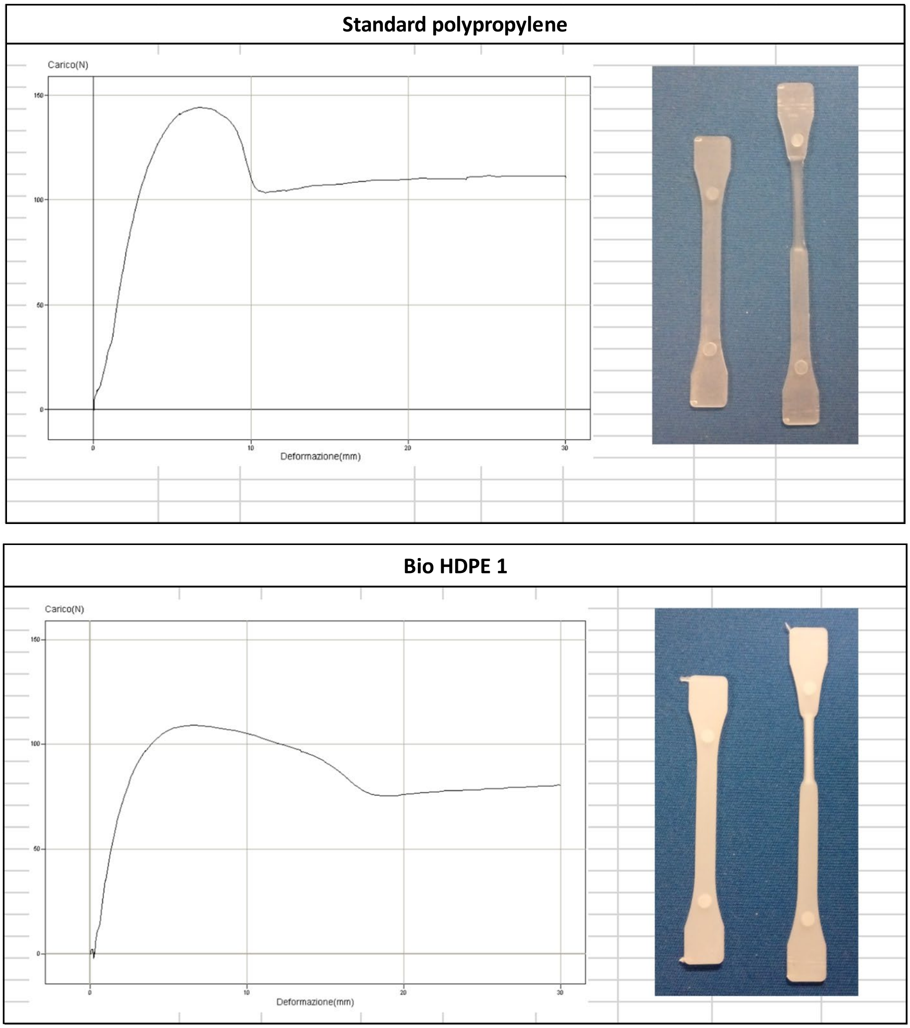


Fig. 7 **a-b** Impact strength results on dog bone specimen

- *Sun resistance test*: also in that case, the results obtained did not show significant differences between conventional plastics and bioplastics.

Discussion

At the end of the tests conducted it has been noted that the overall results obtained by the bio-plastics tested are close to the results obtained by the standard resins, both before storage and after storage *(24 h at 50 °C)*. The weighting of the mentioned aspects leads to considering qualifying for the industrial use, two of the four bio-resins tested (Table 2).

Resin	Standard polypropylene	Bio HDPE 1	Bio HDPE 2 (spess. 1 mm)	Blend of Bio LDPE (15%) and Bio HDPE (85%)
M.F.R. (g/10 sec)	0,21	0,314	0,124	0,336
M.F.R. (g/10 min)	**12,54**	**18,84**	**7,44**	**20,16**
Test representative image				

Fig. 8 Melt flow rate (MFR) index results

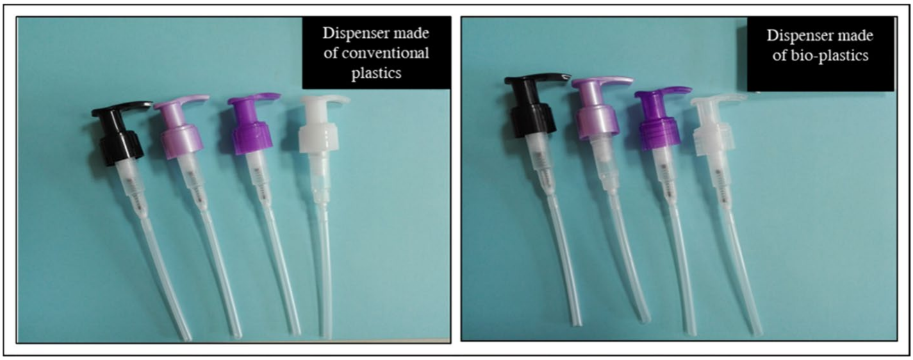


Fig. 9 A comparison of the dispenser made of conventional plastics and the dispenser made of bioplastics with closure, actuator and dip tube in conventional and bioplastics

The table summarizes the results obtained by the four resins compunds in the different tests.

More specifically, the use of Bio HPDE 1 (bio-based content 94%) for closures and actuators for dispenser B has been qualified. The same tests conducted on A dispenser shown a relevant cracking issue between the actuator and the close component. About the results for bio-blend (used for the dip tube extrusion) the test confirmed the suitability of blend of Bio LDPE (20%) and Bio LLDPE (80%) that allowed the producer to finally qualify a new supplier.

The experience gained highlighted also the presence of some additional aspects that can be considered crucial for the diffusion of bio-based materials as substitutes for virgin raw materials at industrial level, among them:

Environmental Performances As far as environmental data is concerned, considering that the production process would remain substantially unchanged as a result of the material substitution (the part of the product system that would change is that of the production of granules of Bio PP and Bio HDPE), a first screening of environmental performances of

Table 2 Bio-resins tested: summary of results and final material qualification

Alternative material	Selected component	*MATERIAL CHECK*	*ALTERNATIVE MATERIAL SUPPLY*	*SPECIMENS MOLDING*	*LAB TESTS*	*COMPONENTS MOLDING*	*DIMENSIONAL TESTS*	*ASSEMBLY TESTS*	*FUNCTIONAL TESTS*	Alternative material qualification
Bio HDPE 1	Closure and actuator	√	√	√	√	√	√	√	√	√
Bio HDPE 2	Closure and actuator	√	√	√	√	√	√	√	√	×
30% Bio LDPE + 70% Bio HDPE	Closure and actuator	√	√	√	√	√	√	√	√	×
30% Bio LDPE + 70% Bio HDPE	Dip tube	√	√	√	√	√	√	√	√	√

the upstream processes was carried out using professional databases (GaBi, 2019). Five midpoint impact indicators (currently available) were used to compare the production of granulate of Fossil-based and Bio-Based HDPE and PP, the functional unit used is 1 unit of dispenser; the Life Cycle Impact Assessment Method is the ReCiPe 2016 [53] (Table 3).

The table shows the results obtained for the five indicators considered in respect of the conventional and the bioplastics analyzed, the unit of measure and related LCIA Method used.

(Source: GaBi Software, 2019) [54]

Although the most commercially used environmental impact indicator (GWP) for both materials is in favor of bio-based plastics (even significantly lower in the case of HDPE) and the same can be said for Fossil Deplation, more contrasting results are obtained for the other three indicators, linked to Water Consumption, Land Use (as expected) and Energy needs connected to the production of raw material granules. The emergence of this type of trade-off represents an important element of reflection for packaging producers and highlights the importance of using multi-indicator assessment methodologies, at least as regards internal strategic choices.

Market Demand Customer demand for bioplastic components is currently still very low compared to the overall volumes of conventional products. This means that company top management is currently not confident in making investments and adopting significant commercial policies in favor of bio-based materials.

Table 3 Impact of the fossil based HDPE and PP materials used for the test compared to bio-based HDPE and PP materials per kg of raw materials

			HDPE		PP	
Impact category	Unit	LCIA Method	FOSSIL BASED	BIO BASED	FOSSIL BASED	BIO BASED
Global Warming Potential	kg CO2 eq	ReCiPe 2016	2,04	1,02	1,95	1,63
Freshwater consumption	m^3		0,01	0,03	0,01	0,03
Land Use	m^2 * year		0,01	1,67	0,03	1,82
Fossil Depletion	kg Oil eq		1,68	0,23	1,60	0,40
Primary Energy Demand	MJ		71,81	154,86	70,32	176,78

Time to Market In terms of time-to-market, the mass-market implementation of material substitution solutions can take significant time (from frist material sample entry to component/product approval), required for research and development, testing, industrialization process and at the end, client validation. Ecodesign strategies must, therefore, include accurate forecasts activities to be able to promptly respond to potential future market requests.

Price Competitiveness Bio-based materials tested often face challenges in achieving price competitiveness compared to conventional plastics due to higher production costs, e.g. associated with renewable feedstocks, refining processes, and limited economies of scale. However, as technology advances and production volumes increase, the gap in price competitiveness is expected to decrease.

Risk of Supply The still low market demand of bio-based materials does not generate particular supply risks in the short and medium term. Nevertheless, it is important to consider that bioplastic production often relies on biomass feedstocks such as corn or sugarcane. Fluctuations in agricultural yields, weather patterns, and competition with other food cultivation are source of criticalities for bioplastic manufacturers. The same applies for potential logistics and transportation problems connected to the long distance that characterize cultivation sites.

Regulatory Aspects It mut be also considered the safety of materials that come into contact with food, drugs and personal care products; the technical data sheets provided by the suppliers contacted during tests demonstrate how, at the moment, the bio-plastics available are compliance with the main European regulations on the food and cosmetic packaging.

Use and End-of-life Further elements of reflection concern to the use phase and the end-of-life of bio-based materials. Laboratory tests and simulations can provide reliable results regarding their performance in use, but cannot guarantee their maintenance and repeatability over time, order after order. This is also connected to the physiological variability of the raw material of biological origin. The same applies to the end-of-life scenarios of bioplastics, which currently vary greatly from country to country.

Availability and Performance of other Substitute Materials In the diffusion of bioplastics, the presence -and prices- of other kind of materials must also be included. In addition to conventional plastics, it is necessary, for example, to consider the prospective developments of other secondary raw materials (e.g. post-industrial and post-consumer plastics). The level of development of recycling technologies and the properties of these materials is growing rapidly and their environmental performances could also be competitive compared to bio-based ones.

Conlcusions

The study presented highlighted the experience gained in the Ecodesign of rigid plastick packaging products—personal care products dispensers- based on the substitution of oil-based plastics with bio-based plastics. The case study described involved a leading company of the packaging industry. The performances of such bio-based materials have been evaluated through laboratory, production and use tests. The activities carried out highlighted that such substitution is technically feasible for the product analized. This indicates that over the last few years, research into these materials has led to a marked improvement in their intrinsic and functional characteristics, which make their marketability much easier. However, in a perspective of sustainable and circular choices, the mass-market production of the dispenser made with the substitute bio- materials also goes through an economic and environmental validation. For confidential reasons, it is not possible to disclose full economic data; however, from the estimates made (based on the average prices proposed by the suppliers), the gap is still relevant in respect of the conventional plastics, but prospective market scenarios are encouraging. The same applies for the environmental performances: the screening analysis conducted confirmed that the substitution of conventional plastics with bioplastics can significantly reduce the GHGs emissions and Fossil Deplation related to the materials considered (PP and HDPE), but the same cannot be said for other environmental impact indicators such as Water Consumption, Land Use and Energy needs. Other empirical insights that emerged during the study concerns decision-making elements typical of the industrial world, which however can significantly impact the prospective diffusion of bio-based materials, for example: the current market demand of such materials, the time-to-market required for their mass-market use, the prospective risks of supply, the regulatory aspects, the management of the end-of-life phase. An aspect considered of particular interest, both for the purposes of an exhaustive overview relating to substitute materials in the plastic packaging industry and also for an industrial purpose, is linked to recent developments relating to the availability and performance of other substitute materials, such as the recycled post-industrial and post-consumer plastic wastes, perspective towards which the future developments of the study could be directed.

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Declarations

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