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Plastics in a circular economy: Mitigating the ambiguity of widely-used terms from stakeholders consultation

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ABSTRACT

This study aims to examine, through stakeholders consultation, the widely used definitions of four terms related to plastics sustainability: ‘bio-based plastics’, ‘bioplastics’, ‘biodegradable plastics’ and ‘plastics recycling’ and to mitigate their potential ambiguity for diverse scientific communities and sectors of activity. For the three terms ‘bio-based plastics’, ‘biodegradable’ and ‘recycling’, consolidated definitions were elaborated based on the feedback of online survey and analysis of the pro and con arguments given by face-to-face interviews with 18 experts followed by an online survey of 122 stakeholders. Acceptance of the consolidated definitions was higher than the official ones with an increase of acceptance from 43% to 81% for bio-based plastics, from 47% to 61% for biodegradable plastics, and from 28% to 60% for plastics recycling. The terms ‘biodegradable’ and ‘recycling’ remain ambiguous even after consolidation of the definition. This highlights that more discussions are necessary to achieve a consensual and fair definition of such complex properties and mechanisms. In the term ‘Bioplastics’ the prefix ‘bio’, referring either to the origin of the resources or the end of life of the material, remains difficult to understand and we prefer to advise against its use, especially with non-expert people (e.g. consumers and the public at large), in favour of the use of ‘bio-based plastics’ or ‘biodegradable plastics’. The issue of this study is to help consolidate wider efforts to develop new strategies for replacing oil-based plastics and improving end-of-life options.

1. Introduction

Plastics are ubiquitous in our everyday lives and are widely used in almost every industry, from vehicle manufacturing to clothing and food packaging. In 2017, the production of plastics worldwide came to more than 359 million tons, which equates to 11 tons per second and about 68 kg of plastic per person per year (Geyer et al., 2017). Plastics consumption in Europe is about 60 million tons per year (Plastics Europe, 2020). Plastics have become so essential to our way of life that fear of oil shortage—and therefore plastic shortage—has spurred intensive efforts to develop and commercialize sustainable bio-based plastic solutions (Kabir et al., 2020; Siltaloppi and Jähi, 2021; Singh et al., 2017; Zheng and Suh, 2019). The appeal of plastics shows no sign of abating, while there is mounting concern around widespread pollution by persistent

plastic waste throughout the environment. Persistent fragmented and pollutant-loaded microplastic and nanoplastic waste has been found in soil (Zhu et al., 2019), air (Sommer et al., 2018), oceans as far as the Arctic (Bergmann et al., 2019), and food chains (Chae et al., 2018). At the outset of the third millennium, the initial fear of a shortage of virgin plastic has moved toward fear linked to plastic omnipresence and the associated risks of accumulation, fragmentation and subsequent spreading of polluting loads of plastic waste in all of the compartments of the Earth (Laskar and Kumar, 2019; Tiller et al., 2019) and into our own human organs (Ragusa et al., 2021; Rahman et al., 2021).

The European Plastic Strategy (European Commission, 2018) is one of many initiatives set up around the world (Xanthos and Walker, 2017) to develop a circular economy for plastic, chiefly by increasing plastics recycling rates and banning single-use plastics. Biodegradable plastics

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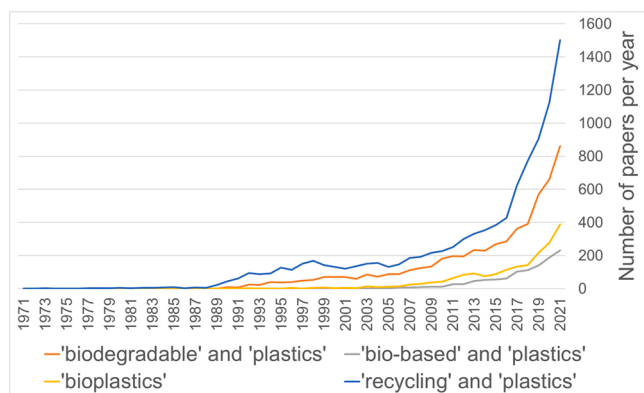


Fig. 1. Number of papers published throughout the years. Papers have been extracted from the Web of Science (“Document search - Web of Science Core Collection” in all databases; 17 January 2022) using a set of Topic keywords of the four terms.

have emerged as another response to address persistent plastic waste in our environment. However, all these initiatives are ultimately weakened by confusion surrounding the definitions and wordings used—typically ‘bio-based plastics’, ‘bioplastics’, ‘biodegradable plastics’ and ‘plastics recycling’. Finally, inappropriate use of one or the other of these terms has undermined stakeholder understanding and confidence in their real benefit.

The surge in papers on these topics since 2000 demonstrates the recent rising importance of these terms (Fig. 1). The term recycling plastics has been first cited in 1971 while bioplastics and bio-based plastics are cited from 1993 and 2000, respectively. However, in all these papers, the same term may be used for processes that, in practice, lead to different effects or products. Recycling, for instance, could be used either to designate a closed-loop process where uncontaminated material with properties close to that of virgin material is recovered (also called primary recycling) or an open-loop process where the material is transformed into lower-quality products (also called secondary recycling, downcycling or upcycling) (Singh et al., 2017). Definition of recycling may also include tertiary (recovery of chemical constituents) and quaternary (recovery of energy) recycling. Analysis of the literature also highlighted a lack of terminological precision with the term ‘biodegradable’. Recently, some plastic bags, claimed to be ‘biodegradable’ were found to have an insufficient biodegradation rate in soil and sea (Laville, 2019; Nazareth et al., 2019; Oakes, 2019). Close examination of these two studies finds that the plastics labeled ‘biodegradable’ were only compostable in industrial conditions (e.g. only at temperatures higher than 58 °C, like for polylactic acid) or oxo-biodegradable (fragmenting into small pieces). The general confusion about what really qualifies as biodegradable material and in what conditions it biodegrades has been a barrier to proper labeling of such products and distorts consumers and industry perceptions about what biodegradable plastic really is.

Finally, inappropriate use of these terms has undermined stakeholder understanding and confidence in their real benefit. Thus, it appears that current definitions consider too broad aspects of the terms ‘biobased plastic’, ‘bioplastics’, ‘biodegradable’ and ‘plastics recycling’ which leads to confusion, mis- or over-interpretation of the terms and the commercialization of plastic solutions without real environmental benefit.

In February 2022, the European Commission has launched a public consultation on biobased, biodegradable and compostable plastics. The consultation aims to provide insight for preparing a new policy framework on these groups of plastics, to address emerging sustainability challenges related to the use of these novel plastics.

The objective of the current study is to clarify the meaning of terms prefixed ‘bio’ (‘biobased plastic’, ‘bioplastics’, ‘biodegradable’) and the

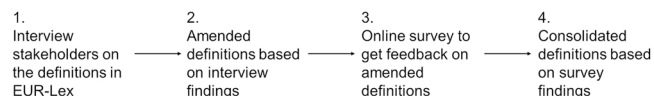


Fig. 2. The four-step method used to situate the definitions of four terms on plastics.

key notion of recycling. With that objective in mind, we start from the ‘official’ definitions of these terms taken from EUR-Lex online gateway (EUR-Lex, 2019) as the main official source of EU legal documents, and from European Bioplastics (EUBIO Admin, 2014) for the term ‘bioplastics’ (as it is not explained in detail in EUR-Lex). A panel of selected experts critically discusses the ‘official’ recognized European definition of the four terms. The definitions are then amended, taking special care to remove ambiguities, and an extended survey is carried out to evaluate the level of acceptance of the amended definitions. Comments and feedback from the survey respondents, especially stakeholders who have rejected the amended definitions, provide elements to be used to elaborate a consolidated definition.

2. Material and methods

We followed a four-step method (see Fig. 2) starting with an ‘official’ definition for each term followed by a series of consultations with domain experts.

Step 1. We consulted a panel of 18 European experienced stakeholders in the field of plastics. We have selected them based on their profiles covering the end-to-end plastics supply chain, from (bio)plastics manufacture via plastics packaging to (bio)waste management. The list included eight academic researchers, six engineers or researchers from large or small private-sector companies, two journalists, one sociologist, and one PhD student. One official definition for each term was selected from EUR-Lex (EUR-Lex, 2019), which provides access to the official and most comprehensive repository of EU legal documents such as Directives and Green Papers, and from European Bioplastics (EUBIO Admin, 2014), which is the association representing the interests of the bioplastics industry in Europe. The opinions of the stakeholders on each ‘official’ definition were collected through short face-to-face interviews lasting around 30 min.

Step 2. We analyzed the findings of these interviews, which revealed agreements and disagreements on several points of the official definitions. We then drafted an amended definition, integrating the opinions and suggestions made by the experts.

Step 3. An extended panel of 122 stakeholders, including those interviewed in step 1, were surveyed via an online questionnaire to get feedback on the amended definitions. Forty-six respondents self-identified as experts and familiar in the field, respectively. The extended panel included 66 academic researchers, 35 engineers or researchers from large or small private-sector companies, 16 other professionals from large or small private-sector companies (consultant, project manager, marketing manager, etc.), two journalists, two PhD students, and a sociologist. The survey was composed of four questions (one question per term). Each item presented both the ‘official’ and the amended definition along with the argument for the modification proposed. For each term, the respondents were asked for two inputs:

A question: “Is the amended definition better than the original one?” which could be answered “Yes”, “No” or “I don’t know”.

A comment: “Please comment on the amended definition proposed and suggest any modifications if needed”.

Step 4. We analyzed the results of the survey, paying particular attention to all comments captured. The results of this survey and the comments of the stakeholders are available in the dataset found at <https://doi.org/10.15454/UUEIQN>. We then drafted a consolidated definition based on the comments associated with answering “No” to the question.

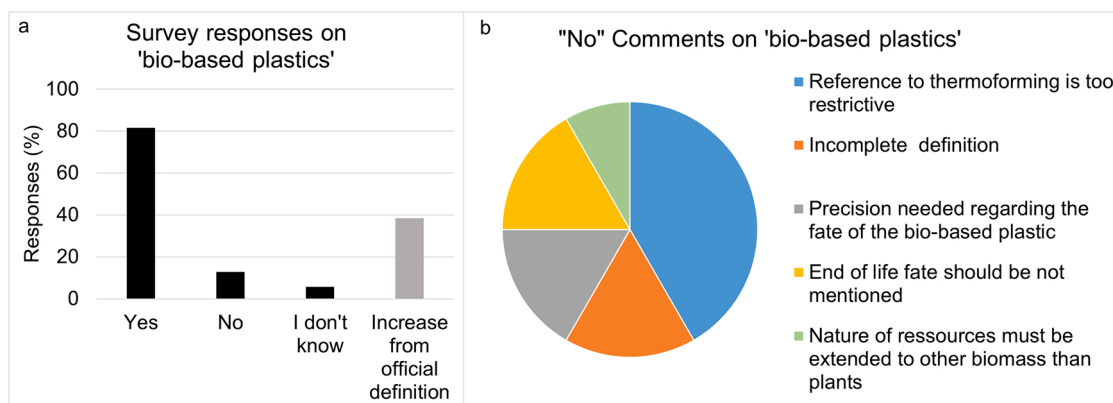


Fig. 3. Analysis of the survey findings on the definition of 'Bio-based plastics'. (a) Percentage of answers to the question "Is the amended definition better than the original one?" and the increase of acceptance from the original to the amended definition. (b) Main comments on "No" answers.

3. Results and discussion

3.1. Bio-based plastics

The first term we considered was 'bio-based plastics'. Its official definition is:

"Current bio-based plastics are usually made from starch extracted from maize, rice, sugar cane or potatoes. Yet, consumers need to be fully informed that this relates to the origin of the resource and not to end of life management." (European Commission, 2013).

Only 43% of the interviewed experts approved this official definition. The interviews highlighted that the main issues were clearly to exclude end-of-life management and to define the notion of fraction of renewable material. Definition improvement was based on two sources: recommendations given in the "Green Paper on a European strategy on plastic waste in the environment" (European Commission, 2013) and annex II of the guidance/policy document "A European strategy for plastics in a circular economy" (European Commission, 2018). The latter is more precise as it also refers to the methodology used to determine the mass of biogenic substances contained in the plastic products, the ISO (International Organization for Standardization) standard 16620-4:2016 (ISO, 2016). According to this last document, "Bio-based plastics refer to plastics that contain materials wholly or partly of biogenic origin".

3.1.1. The amended definition was

"Bio-based plastics are thermoformable polymeric materials produced from biomass resources (such as sugar cane, hydrolyzed maize, rice or potato starch, etc.) irrespective of their end-of-life fate."

Note 1: "Bio-based" refers only to the renewable origin of the resource and not to the end-of-life management and not to organic growing."

Note 2: "Whether the material is not 100% bio-based, the percentage must be added before (e.g. "30% bio-based plastics")."

The amended definition includes the word "polymeric" to better fit with the definition of plastic given in the recent Single-Use Plastics Directive (EUR-Lex, 2019). The word "thermoformable" was added in response to the stakeholder' comments. The part of the definition that reads "Current bio-based plastics are usually made from starch extracted from maize, rice, sugar cane or potatoes" was generalised and replaced by "Bio-based plastics are [...] produced from biomass resources" followed by some examples (i.e. "such as sugar cane, hydrolyzed maize, rice or potato starch"), as suggested by the interviewed experts. In order to make it clear that the prefix 'bio' in "bio-based" does not encompass end-of-life management, note 1 was added to reinforce the end of the

main definition that reads "irrespective of their end-of-life fate". In order to follow Vézina et al.'s recommendations (Vézina et al., 2009) to keep the amended definition simple and clear, the explanation related to the percentage of bio-based materials is detailed in a separate note.

The amended definition was largely accepted by 81% of the survey panelists (Fig. 3a). Only about 12% of panelists rejected the amended definition, for five main reasons (Fig. 3b). The first reason given for rejecting the amended definition is the reference to thermoformable: experts judged it too restrictive to give a definition based solely on thermoformable materials. Indeed, biobased thermoset resins, for instance, are excluded from this definition. The second reason raised is that the definition is still incomplete without more precision while the third reason is related to the origin of the biomass. Indeed, some experts suggested enlarging the nature of the resources so that they would not be limited to the plant storage polymer (starch, sucrose) but could also include micro-algae (e.g. "why not mention micro-algae?"), or animal by-products. Finally, two groups of experts gave contradictory reasons for rejecting the definition: 1) one would like to have more precision regarding the post-usage fate of the bio-based plastic (e.g. "I would indicate the end-of-life fate (if not biodegradable nor recyclable, "bio-based" is confusing"), whereas, 2) one would like to eliminate all reference to the end of life (e.g. "note 1 in the amended definition would not be necessary").

3.1.2. Based on this feedback, we proposed a consolidated definition

"Bio-based plastics are polymeric materials entirely or partially produced from biomass resources irrespective of their end-of-life fate or management and whether they were organically farmed. If the material is not 100% bio-based, the actual percentage has to be prefixed (e.g. "30% bio-based plastic")."

While writing and revising the present paper, EU commission has announced a policy framework on the sourcing labeling and use of bio-based plastics and has launched a public consultation to set up this framework while no EU law is in place yet applying to bio-based, biodegradable and compostable plastics in a comprehensive manner. The EU commission proposes its own updated definition of the term bio-based plastics as "Bio-based plastics are fully or partially made from biological resources, rather than fossil raw materials. They are not necessarily compostable or biodegradable." It is important to highlight that both definitions converge: the consolidated definition of the present work refers to "biomass resources" as the 2021 EU definition refers to "biological resources" and both underlined the fact that the term bio-based is not referring at all to end of life fate. The 2021 EU definition goes even further by adding, "It is important to examine the full life cycle of bio-based plastics, to ensure that they are beneficial to the environment beyond the reduction in use of fossil resources. This includes

littering and changes in land use". However, the 2021 EU definition does not take into account the actual percentage of bio-based material.

3.2. Biodegradable plastics

Biodegradability is the ability of a material to be metabolized as a source of carbon by the microfauna and microflora of the environment under specific conditions. The ultimate biodegradation products are water, gases (CO₂ and/or methane depending on the aerobic or anaerobic conditions met during the process), and a new biomass (Jayasekara et al., 2005). Biodegradability is inherent to organic matter and other natural polymers that can undergo the same biodegradative processes (e.g. biodegradable plastics, paper, cardboard, etc.).

The official definition of biodegradable plastics is:

"Biodegradable plastics shall be understood as plastics that can be degraded by living organisms – in particular microorganisms – into water, CO₂, methane (CH₄) and possibly non-toxic residues (i.e. biomass)." (European Commission, 2013).

Forty seven percent of the interviewees approved the official definition. The comments of the interviewed experts were on two main concepts. First, the term 'biodegradable' should always be associated with first, the surrounding environmental conditions (e.g. medium, temperature and humidity) and second, the duration of the biodegradation process. Both are specified in standards used to assess the biodegradability of a material. These standards are international (ISO) or European (EN) standards and can be divided into two groups as "specification standards" and "evaluation methods". The first group of standards lists the criteria that must fulfill a material to be defined as "biodegradable" (e.g. duration of the biodegradation process and % of biodegradation achieved by this time) whereas the second group describes the method used to assess the biodegradability (e.g. environmental conditions such as medium, temperature, humidity, ratio of medium to material mass, etc.). Evaluation methods differ according to the environment of biodegradation (e.g. anaerobic digestion, industrial or home composting, soil or water) and the biodegradation conditions tested, the couple time-temperature being the most important criteria to reach biological mineralization.

In the present study, biodegradability principally referred, for interviewed experts, to industrial or home composting since they are the main post-usage routes proposed for plastic packaging. It also refers to biodegradability in soil (or natural environment) since littering and accumulation of persistent plastics (and among them packaging) in terrestrial environments is a major concern nowadays. In this context, we will focus on standards permitting to assess biodegradation in soil, industrial and home composting conditions. We will briefly remind below their characteristics, as they are useful to address some of the ambiguity around biodegradation definition.

The most common "specification standards" in the field of food packaging are the famous EN 13432 (EN, 2000) and EN 14995 (EN, 2007) that evaluate the organic recoverability of packaging and plastic materials respectively in industrial composting conditions. For instance, to be considered biodegradable in industrial conditions, a packaging and all its constituents must reach at least 90% of biodegradability in less than 6 months, and only a maximum of 10% of the final compost can be higher than 2 mm size after sieving. In home composting conditions, 90% of biodegradation has to occur in less than one year according to the specification standard NF T51–800 (NF, 2015) while for biodegradation in soil, biodegradation should be at least 90% in less than 24 months (EN/NF, 2018). It is important to highlight that there is no specific standard for packaging biodegradation in soil as this type of item is not intended to be found in soil; indeed, the EN/NF 17033 is for mulching films used in agriculture. However, conditions specified in that standard are often used too for assessing biodegradability of packaging in soil.

Along with these specification standards, "evaluation methods" present practical methods to test the biodegradability, mimicking

industrial or home composting or biodegradation in soil. For instance, the EN/ISO 14855–1, 2013) and EN/ISO 14855–2, 2018) standards describe a method for biodegradation in industrial and home compost, considering that thermophilic conditions (e.g. relatively high temperature) are reached during the process. To mimic industrial composting, biodegradability tests are performed at 58 °C and 55–60% of relative humidity while for home compost, they are performed at 25 °C and 50% humidity. In both cases, the milled test sample is mixed with mature compost with respect to the ratio 1:6 w/w dry matter material/compost.

EN (ISO 17556, 2019b) or the frequently quoted ASTM D5988–96 American standard (ASTM D, 2018) describe methods to assess the biodegradability in soil. ASTM D5988–96 standard specified that the milled test sample is mixed with soil with respect to the ratio 1:250 w/w dry matter material/soil, testing mixture humidity is maintained at 80% and temperature is 25 °C. In EN ISO 17556, the test is performed at room temperature (23 ± 2 °C) and the method is designed to yield an optimum degree of biodegradation by adjusting the humidity of the test soil.

Because the conditions used for each evaluation method are different, a material can be assessed as biodegradable or not depending on the standard used. As an example, materials made of Polylactic Acids (PLA) are biodegradable considering the standard ISO 14855–1 (testing temperature at 58 °C - e.g. above the glass transition temperature of the polymer - in industrial compost) whereas nearly no biodegradation can be seen using the standard 14851:2019 (ISO 14851, 2019a) or 14852:2021 (ISO, 2021; Funabashi et al., 2009; Massardier-Nageotte et al., 2006), that assess biodegradation in mesophilic conditions (20–25 °C) and in aqueous medium. Variability of results between the different standards can also come from the inoculum used for the test. No specification on the type of inoculum to use is required by the different standards that only ask to specify their origin. However, the absence or presence of microbes with the required enzymatic material to hydrolyze a polymer will determine the capability of a packaging to be biodegraded.

We note that beyond biodegradability, three other characteristics are required for industrial or home composting certification such as specified in the EN 13432: disintegration during biological treatment, effect on the biological treatment process and effect on the quality of the resulting compost. Dedicated testing standards exist for all of these three characteristics, which will not be detailed here. It is important at this stage to outline the distinction between compostability and biodegradability that clearly refer to different things even if both terms are overlapping: biodegradability is one of the four characteristics of compostability.

The quick overview of "specifications standards" and "evaluation method standards" well illustrates all the complexity of the notion of biodegradability. Depending on the conditions, a material may biodegrade or not. For instance, industrially compostable material may clearly not be biodegradable in other conditions and especially in natural conditions, while on the contrary, material biodegradable in a natural environment (e.g. soil) is also compostable in industrial composting. This lack of fair and simple link between a term and the corresponding observed effect completely hinders the good understanding of this notion of biodegradability.

3.2.1. The amended definition of biodegradable plastics

In light of all this complexity, giving the fact that standards could not help to increase readability and understanding of the definition, the amended definition of 'biodegradable plastics' was:

"Biodegradable plastics are converted by soil microorganisms in a reasonable time (less than a year), possibly in conjunction with other factors found in widespread natural environmental conditions, into biomass, water, carbon dioxide (CO₂) and methane (CH₄)."

The amended definition is more restrictive than the original one, as a precautionary principle considering that plastics are only biodegradable if they can biodegrade in a natural environment, thus ruling out some materials like polylactic acid, which one could erroneously assume

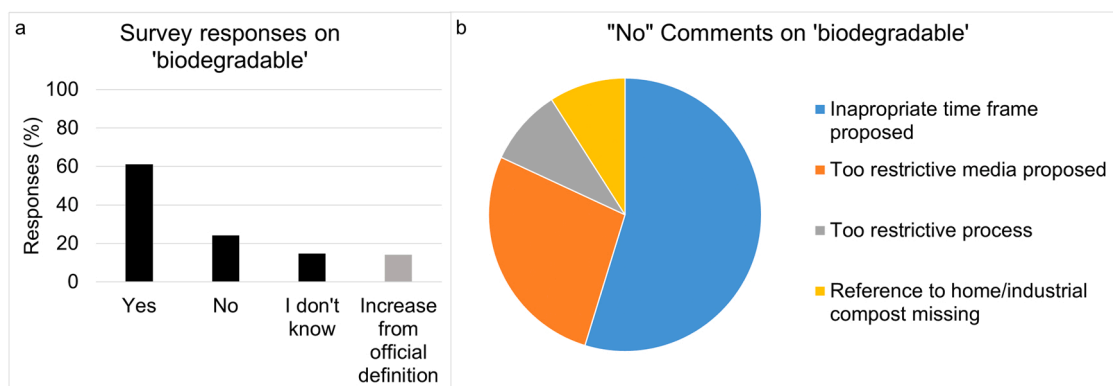


Fig. 4. Analysis of the survey findings on the definition of 'biodegradable plastics'. (a) Percentage of answers to the question "Is the amended definition better than the original one?" and the increase of acceptance from the original to the amended definition. (b) Main comments on "No" answers.

biodegradable in all type of conditions. In addition, improvements to the definition of 'biodegradable' that were requested by the interviewed stakeholders concerned adding a temporal biodegradation horizon and the experimental testing conditions. The amended definition specifies that biodegradation conditions correspond to a natural (and not industrial) environment. It also states that the time required for biodegradation must be reasonable, i.e. no more than a year. For a more accurate definition of 'biodegradable', the boundaries defining biodegradation only encompass plastics that are degradable under natural conditions. Indeed, biodegradable materials that can degrade in the natural environment into molecules (CO_2 , H_2O , and eventually methane and biomass) and in a timespan compatible with human life cycles appear as an asset to solve the issue of plastic littering and accumulation of fine particles in our environment.

The amended definition garnered 61% acceptance from the online survey, which is only a slight improvement compared to the initial official definition (+14%) (Fig. 4a). Twenty two percent of panelists rejected the amended definition, the most cited reason being the inappropriate (too low) timeframe for biodegradation proposed (more than 50% of reasons for rejection; Fig. 4b). Another reason provided was that the biodegradative media used should not be restricted to soil only (30% of reasons for rejection) but extended to other media, such as marine environments for instance. Some respondents also suggested that the process is too restrictive by considering only soil microorganisms as biodegradative conversion agents. They suggested going back to the official definition that mentions "living organisms". Some respondents also proposed to make a distinction between home and industrial composting, which are the two main process routes used to implement optimal biodegradation. Finally, one respondent highlighted that the degradation products of biodegradable plastics are "small non-toxic molecules, water, carbon dioxide, methane". The term "small, non-toxic molecules" appears as an important information to add in the consolidated definition.

3.2.2. Based on the analysis of respondents' feedback, we propose a consolidated definition

"Biodegradable plastics can be totally degraded by living microorganisms (e.g. soil microorganisms) into biomass and small non-toxic molecules such as water, carbon dioxide (CO_2) and/or methane (CH_4) in widespread natural environmental conditions and in a reasonable timeframe compatible with human life cycles."

We decided not to cite the main processes used to implement optimal biodegradation (home-composting, industrial composting, methanization, etc.) in the definition of biodegradable plastics. Because materials are intended to biodegrade in widespread natural environmental conditions and in a reasonable timeframe compatible with human life cycles, this consolidated definition, as the amended one, per se casts away materials that would be solely industrially compostable. Adoption of this

consolidated definition would mean that two distinct categories of materials would prevail in the packaging community, biodegradable plastics and industrially compostable ones, with no overlapping between the two terminologies. We intentionally omitted to mention in this definition the inorganic part that enters in many formulations of biodegradable plastic products, e.g., talc, clays, and other inorganic compounds. Generally, these inorganic compounds are considered as acceptable residues at the end of the biodegradation process. Of course, they must be non-toxic and safe to the environment. The proposed consolidated definition for "biodegradable plastics" did not specifically mention these inorganic compounds but well specified that ultimate biodegradation products are small, non-toxic molecules as should be potential residues. We have chosen to propose a consolidated definition general enough to be well understood by a large audience and that does not enter into too many details and peculiar cases of polymers' formulation. Peculiar cases are matters for "specification standards".

3.3. Bioplastics

'Bioplastics' were initially not dealt with in the first round of interviews because there was no official European definition for them. This is why there is no acceptance figure for the original definition. However, the interviews, focusing solely on bio-based plastics definition, revealed the importance of distinguishing 'bio-based plastics' from 'bioplastics'.

The definition for 'bioplastics' should clearly refer to the origin of the resources and end-of-life management. The term 'bioplastics' per se can prove misleading for consumers and stakeholders as the prefix 'bio' may refer to the bio-based resource only and not to end-of-life management, but it is often understood to refer to biodegradability, which is not always the case (Guillard et al., 2018). Confirming this, a recent online survey made among nationally representative Australians revealed that globally the public's knowledge of bioplastics is low, but perception, particularly of biodegradable plastics, is positive (Dilkes-Hoffman et al., 2019). The association of bioplastic to biodegradable may lead to distorted perception of the real environmental benefit of bioplastics.

Comments made by interviewees confirmed that keeping this ambiguity (are we talking about bio-based plastics or biodegradable plastics, or both?) in the term 'bioplastics' could be problematic. Results of the survey showed that non-academic stakeholders experienced more difficulty understanding terms with 'bio' as a prefix. The 'bio' prefix used in the term 'bioplastics' is often interpreted as meaning 'biological' and, by extension, harmless for the environment, whereas most common 'bioplastics', such as bio-PET (polyethylene terephthalate) and bio-PE (polyethylene), are actually only bio-based and have much the same detrimental impact on health and the environment as their petrochemical-source counterparts.

We proposed a definition inspired from the one proposed by

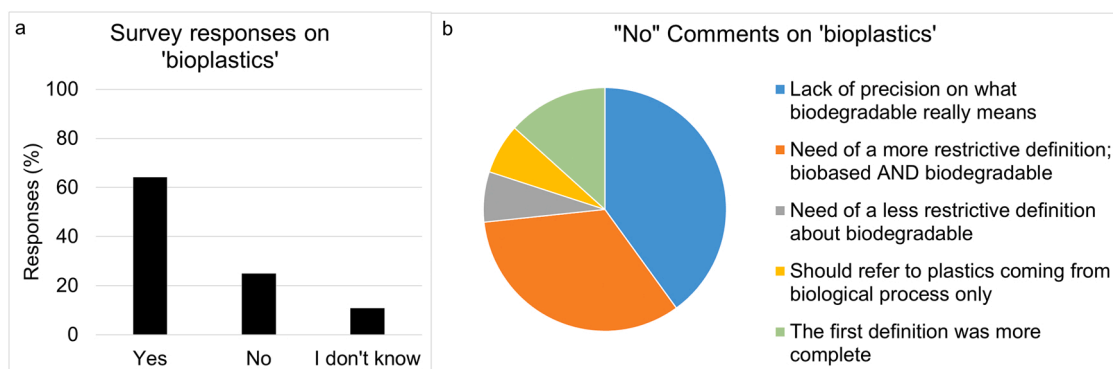


Fig. 5. Analysis of findings on the definition of 'bioplastics'. (a) Percentage of answers to the question "Is the amended definition better than the original one?" and the increase of acceptance from the original to the amended definition. (b) Main comments on "No" answers.

European Bioplastics ("Bioplastics Glossary, 2014), i.e.

"Bioplastics constitute a broad range of materials and products that are bio-based, biodegradable, or both".

Sixty four percent of the surveyed stakeholders approved the definition of 'bioplastics' proposed (Fig. 5a). 25% of them rejected the definition, for two main reasons (40% and 33% of reasons for rejection, respectively): 1) there is a lack of precision about what biodegradable refers to, and 2) there is a need for a more restrictive definition including origin of the resources and the end-of-life fate (biodegradable; Fig. 5b). Indeed, a stakeholder comments: "the amendment continues to associate concepts that are different", which is problematic because we still keep the confusion between bio-based and biodegradable. Another stakeholder also confirmed what was previously highlighted with the interviews: "two different words are needed to distinguish bio-based plastics from bio-based AND biodegradable plastics. Therefore, we can keep the definition of "biobased plastics" for all biobased plastics and use the term 'bioplastics' only for those that meet both criteria."

Based on this feedback, we decided not to propose a consolidated definition of 'bioplastics' as there was no consensus achieved. Instead of rephrasing and changing the definition of bioplastics, the term itself should be changed. A suggestion is to endorse the use of 'bio-based plastics' or 'biodegradable plastics' instead and to not use the term bioplastics anymore.

3.4. Plastics recycling

We then considered the term 'recycling', applicable to plastic, whose official definition reads as follows:

"Recycling means any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations" (Pöttering and Jouyet, 2008).

Acceptance of the original definition was very low (28%). Interviews pointed out that the official definition of 'recycling' is not precise enough for professionals, and especially dealing with plastics. The definition of 'recycling' appears overly general, referring to many types of waste (e.g. metals, nutrients, organic, etc.) and waste components. Plastics recycling can stand for either a closed-loop process where uncontaminated material with properties close to that of virgin plastic is recovered (also called primary recycling), or an open-loop system where the material is transformed into lower-quality plastic product (also called secondary recycling or downcycling) (Singh et al., 2017). Gathering closed- and open-loop recycling routes under the same loose may lead to confusion about the real finality of the processes. In a broad sense, recycling of some plastics could also be extended to the recovery of chemical constituents, e.g. processing waste into fuel, (quaternary

recycling) or recovery of energy (tertiary recycling) or even organic recycling for biodegradable waste (Kumar et al., 2011). However, the products obtained from the starting material are different at the end (compost, fuel, etc.), and gathering all these processes under the same broad term may lead to confusion between the different recycling loops where either the object, the polymer, the monomer or the energy are recovered and reused (Crippa et al., 2019). Plastics recycling is effectively perceived as something positive, and yet consumer understanding of how recyclability works in practice and its environmental impact is globally pretty low (Otto et al., 2021).

3.4.1. Based on this feedback, we proposed an amended definition

"Plastics recycling means any recovery operation, endlessly repeatable, by which plastics waste are regenerated into materials technically indistinguishable from the virgin one.

Downcycling means recovery operation, repeatable several times, by which plastics waste are converted into materials of lower quality or lower value than the virgin one."

To address the main comments of the first round of interviews regarding the definition of 'recycling', the amended definition differentiates 'recycling' from downcycling. First, it states that recycling must be indefinitely repeatable to meet the need for a circular economy, which stands apart from downcycling. Second, recycled material must be technically indistinguishable from the original one. The "endlessly repeatable" characteristic excludes, at the time being, the mechanical recycling of plastics which does not comply, within its current limits, with such definition. For instance, the mechanical recycling of PET bottles into similar PET bottles is possible only for a limited number of cycles (Barthélémy et al., 2014). Chemical recycling, where monomers of plastic could in theory be recovered an endless number of times would better comply with the amended definition.

An example of downcycling would be the emblematic case of most PET bottles, trays and other objects as they essentially serve to make textile fibers that will end up in our clothes to replace cotton and are no longer further recyclable. Other plastics such as polypropylene would end as gardening items, which are then no longer recyclable. Again, this is clearly downcycling. The interviews highlighted the need to add this notion of downcycling where the material cannot be recycled into its original application but can be recycled for another purpose, although its properties, and hence the value of the material, are reduced. The amended definition also covers organic recycling of biodegradable plastics that reintegrate the natural carbon cycle through home composting and photosynthesis to produce new similar biomass.

Like the official definition, the amended definition does not include energy recovery, as the process is not endlessly repeatable. Note that the amended definition does not use the terms "closed loop" and "open loop" in order to avoid any conflict with the definitions given by the European Commission and the European Food Safety Authority for PET

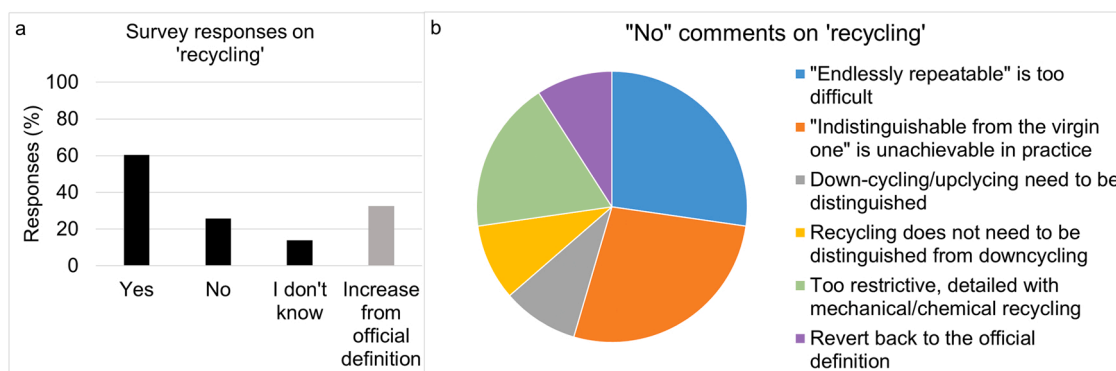


Fig. 6. Analysis of the survey findings on the definition of 'recycling'. (a) Percentage of answers to the question "Is the amended definition better than the original one?" and the increase of acceptance from the original to the amended definition. (b) Main comments on "No" answers.

recycling, which need to be specifically evaluated by the procedure followed here.

The amended definition was approved by 60% of the stakeholders, against 28% for the official definition (Fig. 6a). Among stakeholders who disagreed with the amended definition, about 20% rejected the idea of "endlessly repeatable" and 20% rejected the concept of "indistinguishable from the virgin one" because they felt that both are unachievable in practice (Fig. 6b). Other reasons cited for rejection were that the amended definition seems too restrictive ("no distinction between mechanical and chemical recycling made for instance") (15%), not precise enough ("downcycling and upcycling should be clearly distinguished") (7%) or, conversely, too detailed ("recycling and downcycling do not need to be distinguished") (7%), and one expert recommended keeping the official definition.

A recycled plastic is effectively very rarely indistinguishable from the virgin one due to the degradation of polymers chains and additives. Moreover, losses in the recycling processes mean that the cycle is not truly endlessly repeatable. "Endlessly repeatable" means that the recycled material could undergo the process an infinite number of times without significant degradation of its properties. For example if 33% of losses occur at each recycling cycle, the plastic can be recycled only two times as almost 100% of the matter has been lost at the third cycle. Therefore, these two affirmations of "indistinguishable from the virgin one" and "endlessly repeatable" should be modulated. Furthermore, it appeared important to keep the term downcycling that refers to the post-usage fate of most plastics. It was also suggested to add the term 'upcycling' meaning that the plastic waste can be converted into materials with higher value than the virgin one. However, this definition would refer to the creation of economic value instead of environmental benefits. Taking into account this confusion, the authors recommended not using the term 'upcycling'.

3.4.2. Hence, we proposed a consolidated definition

"Plastics recycling means any recovery operation by which plastic waste is reprocessed into plastics technically very close to the virgin one and enabling final products with the same original purpose and function. If the process losses significantly differ from zero, the number of possible cycles is limited and must be specified.

Plastics downcycling means a recovery operation, repeatable several times, by which plastic waste is converted into materials of lower quality than the virgin one."

4. Conclusions

The face-to-face interviews have clearly highlighted the complexities of the current definitions and revealed their inconsistencies or ambiguities, especially surrounding the use of the prefix 'bio', which can allude to several different meanings. Amendments were suggested and

subsequently assessed using an enlarged online survey. Consolidated definitions were then elaborated in an effort to eliminate most remaining ambiguities. The approach, combining a first round of face-to-face interviews with experts and a second round of a large online survey of diverse stakeholders, has confirmed the importance of the multi-actor approach involving people from different horizons and backgrounds.

Bio-based plastics' clearly refers to the origin of the resource while 'biodegradable' and 'recycling' (including up-and down-cycling) refer to material end-of-life management. The only term that simultaneously refers to both aspects is 'bioplastics', which is also the term that the experts found the most ambiguous. The term 'Bioplastics' remains difficult to understand and it is clearly concluded to avoid its use, especially with non-expert people (e.g. consumers and the public at large). The terms 'biodegradable' and 'recycling' remain ambiguous even after consolidation of the definition. This highlights that more discussions are necessary to achieve a consensual and fair definition of such complex properties and mechanisms. It may be objected that both terms are interconnected considering that biodegradation should be considered as a perfect recycling of biodegradable plastics that reintegrate the natural carbon cycle through home composting and photosynthesis to produce new similar biomass.

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CRediT authorship contribution statement

Sophie Aubin: Methodology, Supervision, Writing – original draft Writing – review & editing. **Johnny Beaugrand:** Conceptualization, Validation, Formal analysis, Investigation, Supervision, Project administration, Funding acquisition. **Marie Berteloot:** Data curation, Investigation. **Rachel Boutrou:** Writing – original draft Writing – review & editing. **Patrice Buche:** Software, Data curation, Conceptualization, Supervision, Writing – original draft Writing – review & editing. **Nathalie Gontard:** Conceptualization, Funding acquisition, Investigation, Resources, Methodology, Supervision, Validation, Writing – original draft. **Valérie Guillard:** Formal analysis, Validation, Visualization, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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