Biodegradability of plastics in the open environment

Mapping review

SAPEA

Science Advice for Policy by European Academies

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Version history

Version	Date	Summary of changes
1.0	~8 February 2021	First published version

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About SAPEA

SAPEA (Science Advice for Policy by European Academies) brings together outstanding expertise in engineering, humanities, medicine, natural and social sciences from over 100 academies, young academies and learned societies across Europe.

SAPEA is part of the European Commission's Scientific Advice Mechanism. Together with the Group of Chief Scientific Advisors, we provide independent scientific advice to European Commissioners to support their decision-making. We also work to strengthen connections between Europe's academies and Academy Networks, and to stimulate debate in Europe about the role of evidence in policymaking.

SAPEA is a consortium of five Academy Networks:

- Academia Europaea
- ALLEA: the European Federation of Academies of Sciences and Humanities
- EASAC: the European Academies Science Advisory Council
- Euro-CASE: the European Council of Academies of Applied Sciences, Technologies and Engineering
- FEAM: the Federation of European Academies of Medicine

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Introduction

Specialists in systematic review at Cardiff University carried out a mapping review of recent research evidence within the field of biodegradability of plastics in the open environment. This literature review was designed to provide supplementary information support for the SAPEA Working Group and forms a separate but complementary document to the SAPEA Evidence Review Report (SAPEA, 2020).

Aims of the mapping review

A mapping review is a systematic search of a broad field, in order to identify where the published evidence exists and where the gaps are. It can also indicate future research needs. It should enable the reader to quickly assess the volume of recent evidence on the topic, the type of evidence, what it covers and where the gaps are in the evidence base.

Review question and scope

This mapping review is linked to the evidence review undertaken by SAPEA to inform the Scientific Opinion of the European Group of Chief Scientific Advisors (the 'Advisors') (SAPEA, 2020). It addresses the main scoping question taken up by the Advisors, which is:

> From a scientific point-of-view and an end-of-life perspective, and applying to plastics that biodegrade either in the terrestrial, riverine or marine environments, and considering the waste hierarchy and circular economy approach:
>
> What are the criteria and corresponding applications of such plastics that are beneficial to the environment, compared with non-biodegradable plastics?

'Biodegradable plastics' is not a clearly defined term and many claims of biodegradability have been made in the scientific literature. Merely reporting weight loss is not a sufficient proof of biodegradation, for example, and this is covered at some length in the SAPEA Evidence Review Report (SAPEA, 2020). Similarly, this review does not assess the use of terms in each reported article, such as whether the form of 'biodegradation' defined by the author(s) meets the criteria established in the Evidence Review Report. This review is not able to distinguish between terms like 'biodegradation' or 'degradation', as these can sometimes be used interchangeably in the literature. Instead, as agreed with the SAPEA Working Group, this mapping review is designed to summarise recent research evidence in relation to a range of 'biodegradable' plastics designated as potentially in-scope at the outset of the Working Group's discussions; see Annex 1 (p.69). These are bio-based plastics, rather than fossil-based.

The Working Group subsequently honed the focus of its Evidence Review Report, once it had reached consensus on its definitions of the terms 'biodegradable plastic' (regardless of being bio-based or fossil-based) and of 'open environment' (SAPEA, 2020). This mapping review is complementary to the Evidence Review Report in providing a broad overview of research activity (in laboratory, composting and open environment settings) in relation to the plastics originally defined as potentially in-scope, and a brief summary of recent research findings. It is important to note that the results described in this report do not necessarily meet the Working Group's final definition of 'plastic biodegradability in the open environment', as set out in the published Evidence Review Report. For example, the focus of the Evidence Review Report on open environments means that, unlike this mapping review, managed waste streams like industrial composting are outside of scope.

The Review Team has described the method of approach, for example, on testing for biodegradability, where it is known; however, this does not imply that it necessarily complies with the testing standards agreed by the Working Group to ascertain biodegradability in the open environment. Nor is the rate or amount of biodegradation necessarily given. Furthermore, the use and impact of additives to polymers are not detailed, unless mentioned in the abstract. A compilation of the literature findings is useful but is to be treated with some caution, in that it should be read in conjunction with the Evidence Review Report (SAPEA, 2020).

Methodology

Adopting a systematic search approach, this paper summarises findings from comprehensive literature reviews published since 2015 and primary research studies published since 2019, in relation to the chapter headings for the Evidence Review Report (SAPEA, 2020).

Search strategy

The search strategy (see Annex 2, p.70) was developed from terms identified from several sources. These included the scoping paper; terms relating to the topic and biodegradable plastics, taken from the early draft of the Evidence Review Report; and terms on the open environment identified from a text analysis of relevant abstracts identified by members of the SAPEA Working Group and other experts. The search strategy was specifically designed to pick up relevant research, while minimising out-of-scope research such as specialist biomedical and bioengineering applications. Supplementary searching was also carried out to maximise the retrieval of relevant research studies.

Study selection

Following completion of the search and deduplication, records were assessed for relevance, using the inclusion criteria (see Appendix 1). In brief, studies were selected if they included specific information on one or more of the 'biodegradable' polymers, as described in Appendix 1, and the report included research of direct relevance to open environment settings. All records were assessed by two reviewers independently, via abstract review for relevance to the topics to be covered by the Evidence Review Report. Studies were grouped into chapter headings, for easy access by members of the Working Group. The database included digital object identifiers (DOIs) for each paper (where available) and live links are provided in the reference list at the end of this paper.

Data extraction and synthesis

In the narrative, a brief summary of the findings from the studies was listed under each chapter heading, based largely on information provided within the abstracts, or full text in the case of the comprehensive reviews.[1] Only peer-reviewed publications were included, but **no formal critical appraisal** was undertaken. The summary of findings is grouped into themes and includes areas of consensus across the recent research literature, as well as

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[1] The authors of the review article indicated that the review was comprehensive and an extensive reference list was included in the publication.

noting any gaps in the evidence. Where known, the method of testing used in each study is provided.

Expert guidance and advice

The mapping review process was supported by an Advisory Group, composed of:

- Professor Ann-Christine Albertsson (Chair of the SAPEA Working Group)
- Professor Wouter Poortinga (Member of the SAPEA Working Group)
- Professor Isabelle Durance (Cardiff University)

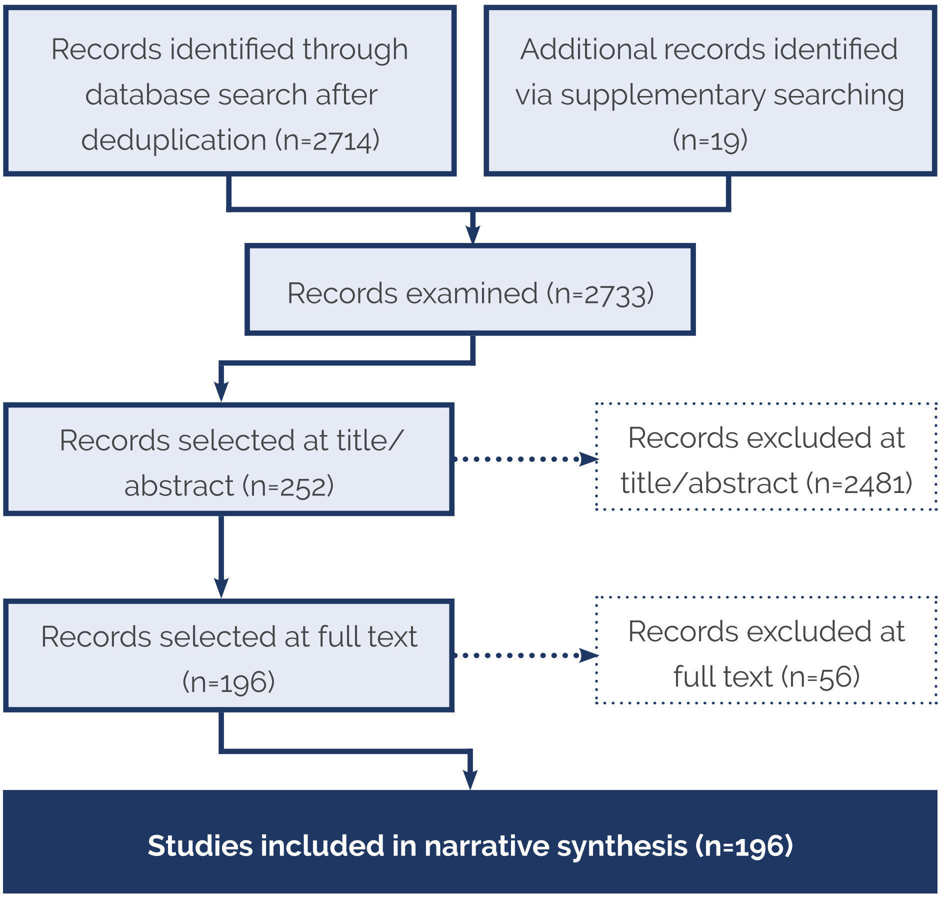
A final draft was reviewed by Dr Costas Velis (University of Leeds) and Dr Gabor Lovei (Aarhus University).

Results

Overview

Of 2733 records identified by all components of the search, 196 met the inclusion criteria and were included in the review.

Figure 1. Flow diagram



To follow the chapter structure of the Evidence Review Report, and to group the findings in a concise and coherent way, they are presented as a narrative, with summary tables and some illustrations taken from the included papers.

Setting the scene: 'Biodegradable' plastics as materials (Chapter 2 of the Evidence Review Report)

This section presents the research on a set of 'biodegradable' plastics as materials, reflecting the variety of recent studies in this area. As per the protocol established for this review, the polymers included in the scope were polyethylene succinate (PES), polybutylene succinate (PBS), poly(butylene succinate-co-butylene adipate) (PBSA), polybutylene adipate terephthalate (PBAT), polycaprolactone (PCL), polylactides (PLA), polyhydroxyalkanoates (PHA) and thermoplastic starches (TPS) (see Annex 1, p.69). The literature identified focused predominantly on PLA, PHA and TPS, with PLA and TPS rarely examined as pure polymers.

Most research focused on the development of composites (primarily of PLA) to provide improved biodegradability and mechanical properties. In line with current standards and testing protocol for biodegradability, the vast majority of the studies below were carried out under controlled and idealised laboratory conditions. As such, the biodegradability of the materials discussed (as with any materials deemed 'biodegradable') cannot be extrapolated to open environment conditions. Rather, this section presents a broad picture of the recent research relating to the in-scope biodegradable plastics, so as to identify key directions and gaps, while a separate section (p.19) presents the research on their biodegradability in the open environment specifically.

Biodegradable plastics as materials	**Number of papers**
Thermoplastic starch (TPS)	12
Polylactic acid (PLA) composites	29
◗ PLA/TPS composites	7
◗ PLA/Lingin/cellulose composites	5
◗ PLA/wood flour composites	5
◗ Other PLA composites/blends	6
◗ PLA nanocomposites	6
Bacteria involved in the degradation of PLA	12
Polyhydoxyalkanoates (PHA)	10
Other biodegradable polymers	6
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Thermoplastic starch (TPS)

Starch is a relatively abundant, low cost, renewable organic material, which has the potential to biodegrade under a range of environmental conditions and, in some cases, in open environments such as soil, as well as home compost (Rujnic-Sokele & Pilipovic, 2017). However, its poor moisture barrier and mechanical properties, low processing temperature and UV susceptibility have led to a significant body of research examining the potential for its reinforcement through adapting processing methods or blending with other materials (Abdullah, Putri, Fikriyyah, Nissa, & Intadiana, 2020; Quispe, Lopez, & Villar, 2019). In terms of the former, research has found that different processing methods, such as melt mixing, solution casting, or a combination, can strongly influence material plasticisation, homogeneity and morphology, in turn influencing the material properties and biodegradability of the TPS produced (supposedly demonstrated by signal intensities and weight losses derived from FTIR and TGA, respectively) (Nevoralova et al., 2019). Further, the use of acetylated starch leads to a reduction in water content, with biodegradability directly correlating with degree of substitution (Nevoralova et al., 2019). The use of different glycerol proportions in the plasticisation of starch (extracted from pasta production by-product) has also been found to impact on tensile strength, elongation at break, total soluble matter released, and glass transition temperature, demonstrating a significant connection between biodegradability and plasticiser (as demonstrated by FTIR, DSC) (Zouari-Ellouzi et al., 2019).

Different starch sources have been demonstrated to significantly influence the nature of polymer films produced. Datta and Halder (Datta & Halder, 2019) found that solvent casted films made from potato starch produced uniform, thin, transparent films, while corn starch films had higher biodegradability (mass loss, swelling index, haze, transmittance, gloss). Datta and Halder (Datta & Halder, 2019) also found that conventional plastic LDPE films degraded faster than both solvent casted starch films in soil.

A range of reinforcing agents have been studied in attempts to improve the mechanical performance of TPS, sometimes reducing enzymatical biodegradability in the process (Leppänen, Vikman, Harlin, & Orelma, 2020). These are listed briefly to illustrate current research trends:

- Blending corn TPS with catalysts (chromium octanoate) enabled film systems to be used as shape memory materials (useful for packaging). Resulting films were found to be biodegradable, but not all safely compostable, as demonstrated by plant growth test (no testing information) (Herniou-Julien, Mendieta, & Gutierrez, 2019).
- Methacrylic acid (MAA), was found to increase graft polymerisation, reduce crystallinity, increase strain at maximum load, and reduce water uptake under soil burial test conditions (Weerapoprasit & Prachayawarakorn, 2019).
- Microcrystalline cellulose (MCC) increased water contact angle and density, decreased moisture content and increased tensile strength (20%MCC optimal) as well as increasing microbe growth, and therefore biodegradability ((Abdullah et al., 2020)- no testing information).

Evidence gaps

As all of the above materials were tested under idealised laboratory conditions (where abstracts specified), and in some cases relying on weight loss as a measure, biodegradability in the open environment cannot be extrapolated. While TPS itself may be biodegradable under a wide range of controlled or 'natural' conditions (Rujnic-Sokele & Pilipovic, 2017) TPS blends/composites are not necessarily biodegradable in open environments or unmanaged composting conditions (Datta & Halder, 2019). Julinová et al (Julinová et al., 2020) demonstrated that, even where TPS blending increases biodegradability, diverse conditions in the open environment can have a strong effect on biodegradation (particularly the absence or presence of high temperatures and humidity). No research was carried out in aquatic environments, or conditions simulating these.

Polylactic acid (PLA) composites

PLA is the most widely-used potentially 'biodegradable' polymer, as it is relatively durable and cost-efficient to produce (Karamanlioglu, Preziosi, & Robson, 2017). It is primarily designed to biodegrade under industrial composting conditions, with limited biodegradability in the open environment (Karamanlioglu et al., 2017). Consequently, all of the studies identified have examined the potential of blends/additives/composites to increase the 'biodegradability' of PLA (according to the definition and testing standard adopted by the author(s)).

PLA/TPS composites

Research examining PLA/TPS blends found that PLA offered mechanical advantages, while TPS helped to address the relatively low biodegradability of PLA in many environments (Rogovina et al., 2019; Taiatele et al., 2019). A composite of TPS (rice straw) and PLA demonstrated significantly increased biodegradability in soil, compared to neat PLA (indoor biodegradation test on samples for 128 days — weight loss, water uptake, visual observations and crystallization investigated). Biodegradability was further increased by the treatment of rice straw (creating pulp and liquor) by alkali pumping and benzylation (destroying hydrogen bonding, dissociating cellulosic component of rice straw from lignin) (Zandi, Zanganeh, Hemmati, & Mohammadi-Roshandeh, 2019). Another TPS/PLA composite, using soy-protein concentrate, was enhanced by the addition of diphenyl methane diisocyanate, leading to a significant increase in biodegradation rate compared to that of neat PLA, due to porosity and increased hydrophilicity ((Liu et al., 2019) — no testing information). TPS blended with PLA was also found to accelerate biodegradation in compost, without negatively affecting compost quality ((Taiatele et al., 2019) — no testing information). In an adiabatic reactor (controlled, thermophilic composting), TPS (isolated wheat starch, plasticised with glycerol) increased PLA biodegradation, by providing a carbon source for microorganisms, and vapour permeability that increased microorganism access to other materials in the blend (Bulatović et al., 2019).

PLA/Lignin/cellulose composites

Da Silva et al (da Silva, Menezes, Montagna, Lemes, & Passador, 2019) highlight the significant potential of lignin to promote PLA biodegradation in garden soil (buried in aquarium apparatus and kept at room temperature with humidity controlled and samples removed at 0, 30, 60, 90 and 180 days). 10 wt% was found to be the best ratio of lignin:PLA, allowing the latter's mechanical properties to be retained, while increasing biodegradability. Lignoceullistic PLA composites made from coir and pineapple leaf fibres were also found to significantly increase biodegradability compared to pure PLA in soil burial and accelerated weathering tests, but with environmental conditions playing a key determining role (Siakeng, Jawaid, Ariffin, & Sapuan Salit, 2019). Rajesh et al (Rajesh, Ratna Prasad, & Gupta, 2019) found that the use of untreated sisal leaf fibre (UTS) in PLA composites significantly increased biodegradability in soil, compared to both neat PLA, and PLA with alkali treated leaf fibre (weight loss, mechanical strength and surface roughness before and after soil burial test). Therefore, fibre loading and alkali treatment could both be used as measures to control biodegradation rates in relation to a desired application. Finally, a study examining the properties of PLA filled with different loadings of hydrophobic cellulose/SiO2 found that low percent loadings resulted in poor mechanical properties, but by 10wt%, properties matched neat PLA. SiO2 addition at high percent loading was demonstrated to hold potential for increasing landfill degradation due to the enzymatic hydrolysis of cellulose, producing lactic and silicic acid, thus catalysing hydrolytic degradation ((Lertphirun & Srikulkit, 2019) – no testing information and not open environment).

PLA/wood flour (WF) composites

The addition of WF was found to increase the biodegradability of PLA in several studies. A composite of PLA/wood flour/polymethyl methacrylate subjected to hydrolysis testing had a hydrolysis rate over eight times higher than that of pure PLA (Wan, Li, Sun, Zhou, & Zhang, 2019). Polylactic acid/wood flour/polymethylmethacrylate (PLA/WF/PMMA) composites studied using FTIR, DSC, universal mechanical properties test and melting index test were found to have enhanced tensile strength, flexural modulus, and hydrolysis rate in relation to pure PLA (Wan, Zhou, & Zhang, 2019). In another study, the thermal modification of wood filler in a PLA/WF composite enabled the control of biodegradation rate and tensile strength depending on required characteristics, as well as the wood filler reducing overall material cost ((Sabirova, Safin, Galyavetdinov, & Shaikhutdinova, 2019) – no testing information). The addition of WF has also been found to increase biodegradation rates in PHBV (Chan et al., 2019) and PBS (Ludwiczak, Frackowiak, Leluk, & Hanus-Lorenz, 2019), in comparison to those of the pure polymers.

Other PLA composites/blends

A range of studies examined other additives/PLA composites, all enhancing the biodegradability of PLA:

- PLA modified by ferric chloride ($FeCl_3$) resulted in a biodegradation rate ten times that of pure PLA, by bonding with C and O, weakening the ester bond, and initiating the first step of degradation (Li et al., 2020).

- Blending with PBAT was found to increase PLA biodegradation rate in cultivated soil (6 months), but to impair mechanical properties with increased standing time in ambient environment ('aging test') (Han, Yu, Guo, & Chen, 2020).
- Orotic acid acted as a nucleation agent, promoting photodegradation and subsequent biodegradation (as measured by DSC and EPR) (Podzorova, Tertyshnaya, Karpova, Popov, & Iop, 2019; Salac et al., 2019).

PLA nanocomposites

A small body of research examined the incorporation of nanoparticles as a means to increase the biodegradability of PLA, or to control biodegradation rates to suit different applications (Kumar & Maiti, 2016). Luo et al (Luo, Lin, & Guo, 2019) demonstrated that the incorporation of Functionalized Titania Nanoparticles (PLA/TiO2) into PLA could increase biodegradability under controlled composting conditions (90 days) by enabling increased water penetration. Studies have shown that the incorporation of graphene nanoplatelets (Bher, Unalan, Auras, Rubino, & Schvezov, 2019; Scaffaro, Maio, Gulino, & Pitarresi, 2020) or carbon nanotubes (Norazlina et al., 2019) decrease biodegradation rates, however, and broader research highlights potential risks associated with environmental persistence and the impact of nanocomposites on human health (Adeyeye, 2019; Kumar & Maiti, 2016; Norazlina et al., 2019). (See also Chapter 5 of the SAPEA Evidence Review Report (SAPEA, 2020), which covers potential ecological risks).

Evidence gaps

Most of the PLA composites above were tested for biodegradability under idealised, laboratory-based conditions (where specified in the abstract), with the potential for significantly different outcomes in open environments (Lv, Zhang, & Tan, 2019; Salazar-Sanchez, Campo-Erazo, Villada-Castillo, & Solanilla-Duque, 2019; Siakeng et al., 2019). While some studies examined the biodegradability of PLA composites in controlled/simulated soil environments, there is a significant lack of research relating to their biodegradability in open environments. Further, no research was carried out in aquatic environments, or conditions simulating these.

Bacteria involved in the biodegradation of PLA

The identification of specific microbial species found to increase biodegradation rates in PLA has been the subject of a number of studies. PLA biodegrades slowly in many open environments, partly due to its resistance to microbial attack and the absence of PLA degrading microorganisms in receiving ecosystems (Decorosi et al., 2019). As a result, increasing concerns relating to the improper disposal of PLA have led to the exploration of waste management strategies using selected, isolated microorganisms under controlled conditions (Butbunchu & Pathom-Aree, 2019; Decorosi et al., 2019; Tseng, Fujimoto, & Ohnishi, 2019). Since the recent studies identified do not look at microbial activity in open environments, they are listed very briefly below to illustrate current research activity.

Most PLA degrading microorganisms are actinomycetes (members of the phylum actinobacteria), and primarily belong to the family Pseudonocardiaceae (Butbunchu & Pathom-Aree, 2019). While a limited number have been isolated, a range of different methods for selection and isolation are emerging, along with the discovery of other species holding potential for PLA biodegradation ((Decorosi et al., 2019) – isolating bacteria to speed degradation of emulsified PLA in agar plates; mesophilic).

Bonifer et al (2019) found that *Bacillus pumilus* B12 (an agricultural soil isolate), enabled the biodegradation of PLA films of high molecular weight over short timescales (48 hours) through the release of L-lactate monomers. Another Bacillus species was found to increase the biodegradation of PLA reinforced with treated and untreated olive husk flour (mass loss and sugar reduction) (Hammiche, Boukerrou, Azzeddine, Guermazi, & Budtova, 2019). Under aerobic composting conditions (as per ASTM D 5988), the biodegradation rate of PLA was increased by *Berkholderia cepacia* (Jandas, Prabakaran, Mohanty, & Nayak, 2019), as well as probiotic lipase obtained from *Lactobacillus plantarum* (TGA, mass loss) (Khan, Nagarjuna, Dutta, & Ganesan, 2019). *Pseudomonas geniculata* WS3 was also found to increase the biodegradability of PLA, PBS and PLA/PBS composite films in submerged cultures, in a soil burial test under mesophilic conditions (Srimalanon, Prapagdee, & Sombatsompop, 2020).[2]

Evidence gaps

No research examined the potential applicability of isolating PLA degrading microorganisms as a means to increase biodegradability in open environment conditions. One paper outlined research possibilities relating to accelerating the biodegradation of polymers in agroecosystems, by promoting microbial proliferation through the inoculation of soil with earthworms (Sanchez-Hernandez, Capowiez, & Ro, 2020).

Polyhydoxyalkanoates (PHA)

PHAs are natural polyesters produced by certain microorganisms such as bacteria and algae through fermentation (Bandeira, Nunes, Rodrigues, Lobato, & Druzian, 2020; Ratnaningrum et al., 2019). PHA polymers biodegrade into CO2 and water under a broad range of conditions — managed and open environments, aerobic and anaerobic, thermophilic and mesophilic — and are one of the only biodegradable polymers to do so (Albuquerque & Malafaia, 2018; Kumar et al., 2020; Ratnaningrum et al., 2019; Umesh & Thazeem, 2019).

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[2] Several recent studies have examined the use of PLA-degrading enzymes in larger scale, managed environments which are beyond the scope of this review (Hobbs, Parameswaran, Astmann, Devkota, & Landis, 2019; Lomthong, Yoksan, Lumyong, & Kitpreechavanich, 2020; Panyachanakul et al., 2019).

Results

A key challenge in PHA production is the selection of microorganisms with a PHA synthesis and storage capacity sufficient for industrial scale production (Albuquerque & Malafaia, 2018; Argiz, Fra-Vázquez, del Río, & Mosquera-Corral, 2020). One method developed for achieving this involves the sequencing of batch reactors under a feast/famine regime, with settling after the feast phase found to enrich culture by promoting the washout of non-storing bacteria and the removal of carbon sources not contributing to PHA production (Argiz et al., 2020). Vladu et al (Vladu et al., 2019) identified two strains of Pseudomonas spp. as effective sources of medium-chain-length PHAs: *Pseudomonas putida* ICCF 391 and *Pseudomonas fluorescens* ICCF and developed pre-producible bioprocess conditions for biosynthesis; processing of fermentation broth; and polymer composition. *Burkholderia sp.* B73, *Bacillus sp.* B58, *Bacillus toyonensis* B50 and *Staphylococcus cohni* B66 were also identified as PHA producing strains with significant potential, using a gravimetric method with 29 different strains from Indonesian soil (Ratnaningrum et al., 2019).

As well as strain identification, PHA production requires the sourcing of a substrate high in organic content (Kumar et al., 2020). Given that this feedstock can contribute up to 50% of overall production costs (which are currently prohibitively high), waste products from agriculture, food production and wider industry are becoming a popular option, with both economic and environmental benefits (Kumar et al., 2020; Yadav & Pandey, 2020). Potential sources identified in the research include: industrial saline complex wastewater (Argiz et al., 2020); pickle wastewater, due to high organic acid content (Guventurk et al., 2020); and sunflower seed and oil waste — particularly effective with *Cupriavidus necator* IPT 026 and IPT 027, and *Burkholderia cepacia* IPT 400 and IPT 119 (Bandeira et al., 2020). In the Treviso municipality, Italy, an urban biorefinery has been developed for PHA and biogas production from biological sludge and food waste, applying the circular economy concept in practice, and providing insight to the social acceptance of products derived from organic waste (Moretto et al., 2020).

The choice of bacterial strain, substrate and fermentation conditions all contribute to determining the properties of the resulting PHA and this, in turn, impacts on its biodegradability (Umesh & Thazeem, 2019; Yadav & Pandey, 2020). As outlined above, PHA is generally characterised by high biodegradability, but several studies have identified further possibilities for accelerating biodegradation (which occurs primarily through microbial activity). This is achieved through the identification, isolation and purification of depolymerase enzymes that play a key role in PHA hydrolysis, such as[P(3HB)] from *Burkholderia cepacia* DP1, Pseudomonas and Acidovorax (Azura Azami, Ira Aryani, Aik-Hong, & Amirul, 2019; Vigneswari, Rashid, & Amirul, 2019). Mandic et al (Mandic et al., 2019) found that medium chain length PHA biodegradation was enhanced by Pseudomonas and Streptomyces strains grown on waste cooking oil, in a laboratory compost model system, proposing waste management options for both polymers and cooking oils.

Evidence gaps

The majority of recent research on PHAs is related to their production rather than their biodegradability under different conditions.

Other biodegradable polymers

A small number of studies focused on PCL, PBS, PSBA and PBAT. Salomez et al. (Salomez et al., 2019) compared PSBA and PHBV biodegradability under thermophilic composting conditions at laboratory scale. Despite higher crystallinity and molecular weight, PHBV had a faster rate of biodegradation, attributed to differences in the polymer's spatial organisation and crystal morphology. Al Hosni et al. (Al Hosni, Pittman, & Robson, 2019) explored the biodegradation of four polymer discs — PCL, PHB, PLA and PBS. PCL degraded the most rapidly in in soil and compost, over 10 months at 25, 37, 50 degrees C. Mechanical properties of PBSA were improved when blended with PCL, without sacrificing biodegradability (soil burial test) (Nicolino, Passos, & Branciforti, 2019), and Li et al (Li et al., 2019) found that biodegradation rates of PBS and distillers grains composites was increased five-fold by the additives E44 and KH560 (mass loss calculated over 75 days). Kirsh et al (Kirsh et al., 2019) found that the addition of agricultural waste products (beet pulp, cocoa bean shell, rice husk) to corn starch, PCL, increased biodegradation rates (mass loss in composting conditions). Finally, PBAT composites have been found to match or exceed the performance of common biodegradable polymers, but production costs are outlined as prohibitive (Ferreira, Cividanes, Gouveia, & Lona, 2019).

Evidence gaps

Biodegradability tests were carried out under controlled, laboratory conditions. Research opportunities have been highlighted in relation to less common biodegradable polymers such as PBAT, currently facing limitations of cost and scale (e.g. Ferreira et al 2019).

Biodegradability in the conditions of the open environment

Much of the recent research, as described above, has examined biodegradability in controlled, laboratory environments, primarily under thermophilic, aerobic conditions, with some simulating anaerobic conditions or aerobic, mesophilic soil environments. Where testing has been extended into field scenarios, highly variable results have been obtained.

Biodegradability in open soil environments is strongly influenced by temperature, humidity and microbial conditions (Emadian, Onay, & Demeril, 2017; Haider, Volker, Kramm, Landfester, & Wurm, 2019; Karamanlioglu et al., 2017). Plastics including PLA, PHA, starch-based, PBS and PCL are susceptible to biodegradation by compost under specific environmental conditions (such as temperature, pH and moisture content). The differences between home and industrial composting may lead to significant differences in biodegradation, as may different formulations and blends. Differences in soil conditions (such as pH) and different marine environments (supralittoral down to sediment) are also crucial (Emadian et al., 2017).

Many materials certified as compostable in laboratory conditions have been found to show little to no biodegradation in home or agricultural composting environments (sometimes even under industrial composting conditions), and, additionally, have sometimes been found to negatively impact on compost quality (Adamcova, Zloch, Brtnicky, & Vaverkova, 2019). As indicated above, PLA — a product designed to biodegrade in controlled composting conditions — is a particular concern for open environment contamination, due to its increasing production, and its low biodegradability in some terrestrial, and particularly marine and freshwater environments (Karamanlioglu et al., 2017). Further, while TPS and PHA stand out as polymers with higher biodegradation rates than other commercially available materials such as PLA the development of composites/blends to enhance mechanical properties (e.g. TPS/PLA) may compromise their biodegradability, particularly in open environments (Hong & Chen, 2017; Karamanlioglu et al., 2017; RameshKumar, 2020).

Due to the significant uncertainties surrounding the fate of biodegradable polymers in open environments, the literature highlights the potential for new waste management challenges to emerge if appropriate certification systems, facilities, regulation and awareness are not developed (Karamanlioglu & Alkan, 2019; Quecholac-Pina, Hernandez-Berriel, Manon-Salas, Espinosa-Valdemar, & Vazquez-Morillas, 2020).

Evidence gaps

As highlighted throughout this chapter, there is a significant lack of evidence relating to the biodegradability of in-scope polymers in the open environment. While a number of the studies above have examined biodegradability in soil under idealised laboratory conditions, few studies simulated unmanaged environments, and field testing was almost entirely absent. This reflects the current testing protocol for biodegradability, in which performance under diverse/variable open (or simulated) environmental conditions is not considered (Haider et al., 2019). If biodegradability is viewed as a ‘system property’ — determined not only by material properties but also by characteristics of the receiving environment (SAPEA, 2020) this review highlights a significant research gap surrounding the latter environmental factors.

There is a particularly notable lack of evidence relating to aquatic environments. The diversity of aquatic conditions is identified as a central factor determining the biodegradability of polymers in these environments, and as a key challenge in developing research and testing protocols (Beltrán-Sanahuja, Casado-Coy, Simó-Cabrera,

& Sanz-Lázaro, 2020; Chamas et al., 2020; Dilkes-Hoffman, Lant, Laycock, & Pratt, 2019; Dutra et al., 2019; Ren, Hu, Yang, & Weng, 2019).

Applications of biodegradable plastics: considerations relating to environments (Chapter 3 of the Evidence Review Report)

This section describes the recent research relating to different applications for the in-scope biodegradable plastics grouped under the general headings adopted for the Evidence Review Report ((SAPEA, 2020) – Chapter 3): (i) Applications where collection from the environment is challenging; (ii) Applications where separation of the plastic from other organic waste presents a challenge; and (iii) Applications where the benefits of biodegradable plastic use are less clear. The Evidence Review Report provides more details on the applications themselves.

Applications of biodegradable plastics	Number of papers
Applications where collection from the environment is challenging	
Agriculture	30
Building materials	4
Applications where separation of the plastic from other organic waste presents a challenge	
Edible food packaging	3
Cosmetic microbeads	2
Applications where the benefits of biodegradable plastic use are less clear	
Carrier bags	3
Single use packaging	16
Cosmetic packaging	2
Fabrics	4

Applications where collection from the environment is challenging

Agriculture

Agriculture	Number of papers
Agricultural mulch films	23 (3 on sprayable films)
Pesticide or fertiliser release vehicles	2
Seed trays	1
Aquaculture piping	1

Results

Mulch films

Using mulch films made from biodegradable materials such as PBAT or PBSA is considered a more sustainable alternative to the use of PE films, and circumvents costs and labour associated with film disposal (Brodhagen, Peyron, Miles, & Inglis, 2015; Sander, 2019). The following research examined the implications of adopting biodegradable films for crop yield, characteristics, and soil quality. Overall yield was found to be similar for both biodegradable and non-biodegradable (PE) films in a range of contexts: vineyard in Southern France (Gastaldi et al., 2019); pepper production in Spain (Marí, Pardo, Aibar, & Cirujeda, 2020); summer maize production in arid/semi-arid regions (Yin, Li, Fang, & Chen, 2019); and tomato and cotton production in southern Xinjiang, China (Wang et al., 2019; Wang, Yu, Yang, Abdalkarim, & Chen, 2019). In two studies, relating to tomato production in southern Italy and in Jordan, biodegradable mulches were found to produce a higher yield (Alamro, Mahadeen, & Mohawesh, 2019; Sekara et al., 2019).

Across the research a range of additional factors were examined, such as fruit fitness/quality and rootstock development, as well as soil moisture content, temperature, organic content/microbial community and water use conservation. Broadly, biodegradable films were found to perform similarly to PE films in all categories, despite film degradation typically beginning within several months of transplant (Alamro et al., 2019; Gastaldi et al., 2019; Marí et al., 2020; Wang et al., 2019; Wang et al., 2019). In southern Italian tomato production, root growth and fruit quality were improved with biodegradable films (Sekara et al., 2019), and in Jordanian tomato production, all factors were found to be similar or improved for biodegradable films (Alamro et al., 2019).

In some cases, however, the performance of biodegradable films decreased as degradation increased throughout the growing season, though this did not appear to affect overall yield. In Chinese cotton production, soil moisture content and temperature decreased as film biodegradation increased, leading to lower water-use conservation and higher soil salinity (Wang et al., 2019). Similarly, while biodegradable films initially performed better than PE films for soil moisture and temperature in summer maize production, as film degraded throughout the growing season, performance fell to a level similar to PE (Yin et al., 2019). In Spain, film biodegradation was found to be accelerated by extreme wind or temperatures (Marí et al., 2020). In most studies, it was claimed that mulch films had significantly degraded by the end of the growing season, and completely biodegraded within a year (Alamro et al., 2019; Marí et al., 2020; Wang et al., 2019; Wang et al., 2019; Yin et al., 2019). Indeed, one study has highlighted how the existing soil biodegradability testing protocol may be limiting the development of agricultural products suitable for prolonged use (months or years) by favouring fast biodegradation when this is not necessarily optimal for mulch film performance (Šerá, Serbruyns, De Wilde, & Koutný, 2020).

Several studies explored the development of new mulching materials. Given the low uptake of PLA as a mulch film material due to its relatively slow biodegradation in soil (Puchalski et al., 2019), composites have been developed using soy and alfalfa, significantly increasing mass loss and microbial respiration, and reporting complete biodegradation within six months, without compromising crop yield or quality (Redondo, Peñalva, Val, Braca, & Pérez, 2019; Thompson et al., 2019). Some bio-stimulants were found to promote biodegradation by increasing microbial activity. However, evidence is inconsistent (Thompson et al., 2019) and the presence of *B. subtilis* was found to increase biodegradability of both PLA and PBAT films (Morro, Catalina, Sanchez-León, & Abrusci, 2019). Certain additives found to enhance the performance of PLA films include organic fertiliser, by promoting biomass accumulation, and silica rice ash, promoting the structural growth of leguminous plants (Harada, de Souza, de Macedo, & Rosa, 2019). In terms of PBAT films, carbon black fillers are found to impact on biodegradation rate, by mitigating the negative impact of irradiation on enzymatic hydrolysability, reducing photochemical susceptibility (De Ho et al., 2019; Souza, Coelho, Sommaggio, Marin-Morales, & Morales, 2019).

A growing area of research examines the development and performance of sprayable biodegradable polymer coatings (including plastics such as pinoline derivatives and vinyl-acrylic) as a higher performing, lower cost replacement for mulch films (Adhikari et al., 2016). Polymers used in these films are out of scope for this review but are mentioned briefly here as an emerging trend. Studies have found these to be effective for soil moisture conservation (Borrowman, Johnston, Adhikari, Saito, & Patti, 2020; Braunack et al., 2020), temperature control and crop yield (Braunack et al., 2020), but show inconclusive findings for biodegradation rates (Borrowman et al., 2020; Meints, 2020). Sprayable mulch film production is currently limited by high costs, due to low market penetration, but holds potential in terms of reducing farm labour costs (Adhikari et al., 2016).

Pesticide/fertiliser release vehicles

Another use for biodegradable plastics in agriculture identified in two studies was as a pesticide or fertiliser release vehicle. PCL was also found to be effective in encapsulating signal molecules (flavonoids and organic acids) for the interaction between plants and plant growth promoting rhizobacteria, a chemical fertiliser alternative (Cesari et al., 2020). PCL facilitated the controlled release of signal molecules according to a plant's needs, therefore enabling crop growth (e.g. peanut) in adverse environmental conditions (Cesari et al., 2020). Finally, the development of PLA hollow fibres by high speed melt-spinning has been found to hold potential for producing biodegradable alternatives for the encapsulation and delivery of pesticides with the variation of internal and external diameters and material characteristics possible through altering factors such as winding speed, extrusion temperatures and polymer throughput (Naeimirad, Zadhoush, Neisiany, Salimian, & Kotek, 2019).

Other agricultural uses

One study examined the impact of biodegradable seed trays (a blend of PLA, PBAT and starch) on paddy soils' microbial communities, as determined by concentrations of phthalic acid ester (PAE), enzyme activity, and physicochemical properties (Meng et al., 2019). Little evidence of PAE release was identified, and negligible impact on soil quality, with microbial profiling at community level finding increased microbial activity and decreased diversity after 55 days, but no effect after 110 (Meng et al., 2019).

In aquaculture, a study comparing the impact of PVC and PHB pipes on post-larval tiger shrimp (Penaeus monodon) showed survival rates to be significantly higher with PHB, due to increased resistance to environmental conditions and pathogens (Ludevese-Pascual, Laranja, Amar, Bossier, & De Schryver, 2019).

Evidence gaps

There is a lack of evidence relating to the longer-term impact of biodegradable plastics post-soil incorporation (Ghimire, Flury, Scheenstra, & Miles, 2020), and in understanding the influence of specific/context-dependent soil and polymer characteristics and environmental conditions on the biodegradation process (Brodhagen et al., 2015; Ghimire et al., 2020; Sander, 2019; Sintim et al., 2020). Diverse field conditions have been evidenced to significantly impact on biodegradation rates (Puchalski et al., 2019; Sintim et al., 2020), and potential ecotoxicology implications relating to biodegradable polymer microplastics have been highlighted (Haider et al., 2019), such as the increased absorption of heavy metals from agricultural pesticides/fertilisers in PBAT, compared to PE microplastics (Li et al., 2020) (see Section 3.5).

Importantly, very few studies on agricultural mulch films specified the polymers used, instead referring broadly to 'biodegradable mulch films'. These studies had to be considered as out-of-scope for this review.

Building materials

Research on the performance of a PHA wood-plastic composite (WPC) matrix under 'in-service' conditions over a 12-month period, found that mechanical stability was maintained in indoor conditions, partially in outdoor conditions, and complete biodegradation occurred in soil, highlighting the potential for applications requiring time-limited performance (Chan et al., 2020). Adding nanoclay particles and cellulose nanofibres was found to improve the performance of biodegradable WPCs (industrial sawdust and starch thermoplastic polymer) (Saieh, Eslam, Ghasemi, Bazyar, & Rajabi, 2019). A study examining the potential for utilising industrial and agricultural waste in building materials, measured the performance of composites combining PBAT/PLA with wood fibres, textile waste fibres, rice husk or wheat husk (Muthuraj, Lacoste, Lacroix, & Bergeret, 2019). Wood and textile fibres were found to be most compatible, demonstrating good compressive and flexural strength, thermal conductivity and low water absorption, meeting requirements for indoor building insulation (Muthuraj et al., 2019). The use of biodegradable polymers is also found to hold potential in geotechnical and geo-environmental applications, providing a technically viable alternative to synthetic materials such as PP used in geosynthetics (Cislaghi, Sala, Borgonovo, Gandolfi, & Bischetti, 2020). PLA demonstrates suitable mechanical properties for innovative applications such as with live plants, but not enough is currently known about the evolution of these properties in open environments over longer time periods (Cislaghi et al., 2020).

Evidence gaps

No studies meeting the inclusion criteria for this review were identified on fireworks and dolly rope, two other applications considered in the Evidence Review Report where collection from the environment is challenging (SAPEA, 2020).

Applications where separation of the plastic from other organic waste presents a challenge

Edible thermoplastic starch films

Research relating to the development of biodegradable starch films is primarily focused on edible applications (Versino, Lopez, Garcia, & Zaritzky, 2016). An edible film developed for pineapple dodol (a type of confectionery) packaging using heat-moisture treated sweet potato starch (EF-HMT) was assessed against PP packaging, finding lower free fatty acid content and weight loss after five weeks storage, and similar moisture content, texture and colour, proving a technically viable alternative and meeting Indonesian standards (Knapp et al., 2019). Another study assessed the impact of applying different concentrations of yerba mate extract (YME) to cassava starch films, finding that elongation and tensile strength decreased with concentration, but antioxidant activity increased, indicating potential application for the edible packaging of fatty foods (Indrianti & Ratnawati, 2019).

Cosmetic microbeads

A cosmetics application for biodegradable plastics identified in the research is the production of microbeads. PLA pre-treated by electron beam radiation was found to offer a promising alternative to synthetic polymer microbeads, showing biodegradability and low absorption of persistent organic pollutants due to reduced surface area (Nam &

Park, 2019) with similar findings produced by a study examining weight loss in controlled aqueous environments (Nam & Park, 2020).

Evidence gaps

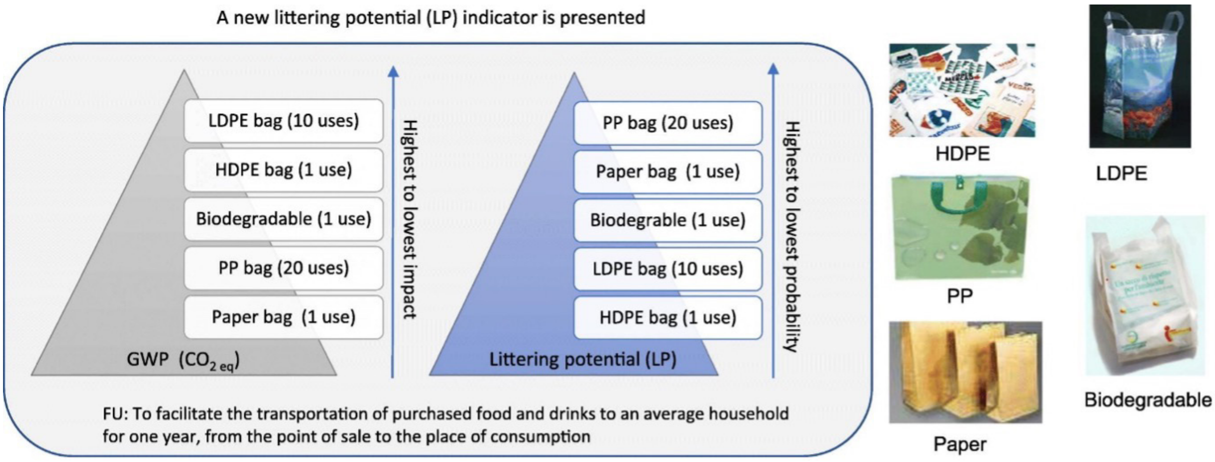
No studies meeting the inclusion criteria for this review were identified on fruit and vegetable stickers or compostable plastic bags, other applications considered in the Evidence Review Report where separation of the plastic from other organic waste presents a challenge (SAPEA, 2020).

Applications where the benefits of biodegradable plastic use are less clear

Carrier bags

Civancik-Uslu et al. (Civancik-Uslu, Puig, Hauschild, & Fullana-i-Palmer, 2019) developed a littering indicator to allow a comparison of littering of plastic bags in the marine environment. The indicator (based on a comparative LCA of HDPE, LDPE, PP, paper and biodegradable plastic bags) is influenced by parameters such as: number of bags to fulfill the functional unit, weight, surface, fee, and biodegradability. The authors note that further research is needed to refine the model and include additional contributing variables. It should therefore be treated with caution.

Figure 2. Littering indicator for plastic bags in the marine environment (Civancik-Uslu et al., 2019)



Recent research has also highlighted the issue of false biodegradability claims in relation to carrier bags (Nazareth, Marques, Leite, & Castro, 2019)[3] and incorrect disposal, even

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[3] This issue has also been raised by Napper and Thompson (2019) (cited in SAPEA 2020) although the composition of the bags was not analysed so it is not possible to know if this paper meets the inclusion criteria for this mapping review. Napper, I. E. and Thompson, R. C. (2019) 'Environmental Deterioration of Biodegradable, Oxo-biodegradable, Compostable, and Conventional Plastic Carrier Bags in the Sea, Soil, and Open-Air over a 3-Year Period', Environmental Science and Technology, 53(9), pp. 4775–4783. doi: http://dx.doi.org/10.1021/acs.est.8b06984

where information is communicated by packaging labels (Taufik, Reinders, Molenveld, & Onwezen, 2020).

Single use packaging

Single use packaging	Number of papers
Starch-PLA composites	8
Nanocomposites	5
Other composites/blends	4

16 research papers explored the application of biodegradable plastics for food packaging. The majority of research explicitly relates to the development and performance of materials, in terms of packaging functionality and biodegradability. In all cases (where specified in the abstract), biodegradability was tested under controlled, laboratory conditions, so cannot be extrapolated to open environment contexts. For further detail, the full text of papers would need to be read and analysed.

Starch-PLA composites

The application of PLA for biodegradable water and food packaging is limited by its low biodegradation rate (Bałdowska-Witos, Kruszelnicka, & Tomporowski, 2020), brittle film structure, and oxygen permeability, while starch is highly sensitive to moisture content and has low mechanical resistance (Mao, Tang, Zhao, Zhou, & Wang, 2019; Muller, Gonzalez-Martinez, & Chiralt, 2017). However, their combination is demonstrated to address some of these limitations, improving performance and reducing production costs (Muller et al., 2017). In some studies, the addition of starch was found to improve mechanical properties such as tensile strength and increase biodegradability (mass loss, TGA) ((Mutmainna, Tahir, Lobo Gareso, & Ilyas, 2019) — starch/chitosan composite; (Marichelvam, Jawaid, & Asim, 2019) — rice starch). The acetylation of starch is shown to improve its compatibility with PLA, as well as its processability, and different degrees of substitution of acylated starch to neat starch were found to produce different properties: and increased transparency and therefore suitability for packaging (Nasseri et al., 2020). Supercritical carbon dioxide (SCCO2) treatment was also shown to improve the performance of a PLA-starch composite (with durian skin fibre, epoxidised palm oil, and cinnamon essential oil as a antimicrobial agent), deceasing water absorption and increasing biodegradability (soil burial test) (Anuar et al., 2020). Blending PLA and starch in different ratios with castor oil and hexamethylenediisocyanate, or epoxidised soybean oil and maleic anhydride have been found to produce particularly high-performing materials for food packaging, providing flexibility, mechanical resistance, competitive cost and suitable food contact properties (Muller et al., 2017). Multilayer films using PLA and starch are also shown to demonstrate good mechanical resistance, as well as barrier capacity for gasses and water vapour, offering a range of applications depending on layer combination, as well as the potential to carry active compounds to provide antioxidant or antimicrobial properties (Muller et al., 2017).

Other composites/blends

Biodegradable polymer blends were found to be significantly better suited to food packaging applications than individual plastics, and have also been developed with PHB, PCL and PHAs and various starch or cellulose materials and additives to improve material characteristics (Albuquerque & Malafaia, 2018; Din et al., 2020). For example, biodegradable films have been developed with essential oil additives to improve fruit preservation by increasing permeability to gas and water vapour (Jiang et al., 2020). Angelica essential oil additive was found to produce the best preservative effect, maintaining moisture, delaying oxidation and extending shelf life (Jiang et al., 2020). Respiration control has also been achieved by utilising the different permeation rates of different biodegradable polymers, enabling the design of materials suitable for limiting microbial growth in different food products (Herrera, Castellanos, Mendoza, & Patiño, 2020).

Nanocomposites

Nanotechnology has also been employed in attempts to produce biodegradable polymer composites that offer improved performance for food packaging. However, the use of nanotechnology in food packaging also presents considerable potential health risks, requiring careful research and the development of new regulatory frameworks (Adeyeye, 2019).

A study on the development of a PLA-based nano composite film — PLA/starch found that nanofibrillated cellulose (NFC) loading reduced shear stress/viscosity and reduced air permeability, showing potential for packaging applications (Mao et al., 2019). The incorporation of different nanofillers (e.g. AgO, TiO2, SiO2, ZnO) to a biopolymer matrix (e.g. PHB, PBS, PLA, PCL, starch, chitosan) improved material mechanical properties and enhanced biodegradability and cost efficiency, as well as increasing shelf-life by incorporating antimicrobial agents that inhibit the growth of different pathogens such as *Listeria monocytogenes* or *Escherichia coli*, and blocking UV radiation (TiO2) (Mohr et al., 2019; Sharma, Jafari, & Sharma, 2020; Tajdari, Babaei, Goudarzi, & Partovi, 2020). However, respirometry tests showed that biodegradation in soil at room temperature for the polymer Ecovio® with incorporated titanium dioxide nanoparticles was not complete at 90 days (Mohr et al., 2019).

Evidence gaps

Other bio-based polymers such as PCL, PBS, PHA and composites are also used in packaging applications, although did not appear in the primary research identified, reflecting the overwhelming market-share of PLA and starch blends (Albuquerque & Malafaia, 2018; Kumar et al., 2020; Sikorska, Musiol, Zawidlak-Wegrzynska, & Rydz, 2019).

Returning to the concept of biodegradability as a 'system property' — determined both by material properties and by characteristics of the receiving environment — the research in this section focuses primarily on the development of materials, with very little attention to possible end-of-life scenarios and how this may impact on biodegradability. In particular, there is no evidence relating to the behaviour or impact of products (largely designed for industrial composting) that end up in the open environment. The research emphasises a significant risk for food packaging applications, due to current limitations surrounding product labelling/certification and disposal infrastructure (e.g. (Haider et al., 2019; Hong & Chen, 2017; Karamanlioglu et al., 2017; RameshKumar, 2020; Sikorska et al., 2019). Din et al (Din et al., 2020) highlight a need for research on the biodegradability of specific materials and composites in a range of potential receiving environments, as well as research into the development of waste management strategies and infrastructure (Din et al., 2020).

Another evidence gap surrounds the 'production end' of biodegradable packaging (and materials more generally). Research on PLA beverage cups (Changwichan & Gheewala, 2020) and olive oil packaging (Giovenzana et al., 2019) have found that PLA does not necessarily represent an environmentally sustainable alternative, when compared to (suitably used) recyclable or re-usable materials such as PE or stainless steel. Such comparison, in particular, depends on the relative impacts of different feedstock sources. Research gaps surround both the impact of land use change associated with the (predominant) use of first-generation feedstocks in PLA production, as well as the potential of non-food crops, waste products and bacteria as alternative feedstocks, and how production costs/impacts may be further reduced by scaling and the use of renewable power sources (e.g. (Bussa, Zollfrank, & Röder, 2019)).

Cosmetic packaging

Biodegradable materials for cosmetics have been created using PHAs, PLA and polysaccharides, and modifications made to meet the requirements of cosmetics preservation in both rigid and flexible packaging (Cinelli, Coltelli, Signori, Morganti, & Lazzeri, 2019). Research on the degradation pathways of PLA and PHA produced by 3D printing for cosmetics, found that PHA degradation was accelerated in environments rich in microorganisms, and PLA degradation was accelerated by paraffin while PHA degradation was slowed (Rydz et al., 2019). However, these findings varied significantly under natural conditions, and the influence of printing orientation on material properties was also found to affect the degradation rate.

Fabrics

Biodegradable polymer fibres can be used in spinning to create textiles, and a range of fibres are available commercially, such as Inego (Natureworks), a biodegradable thermoplastic PLA (Younes, 2017). Biodegradable fabrics are also being produced through the weaving, knitting and non-woven web-forming/bonding of biodegradable polymers (Younes, 2017). A key challenge in the development of biodegradable polymers to replace common fabrics or textiles is ensuring strength, without compromising end of life biodegradability (Younes, 2017). A study on the performance of PLA, lyocell fibre, and PLA — lyocell fibre blends, found that the latter can provide advantages over commonly used PET-cotton blends, not just in terms of sustainability, but in relation to a range of performance parameters such as water vapour and thermal resistance, air permeability, strength and piling propensity (Jabbar et al., 2020). Another study examined a PLA and cellulose acetate composite, subjected to low-temperature alkali/urea treatment for reinforcement (Li et al., 2019). This enhanced tensile strength, compacted structure and increased hydrophilicity. The latter made them more susceptible to biodegradation in water but increased interfacial adhesions strength reduced biodegradation potential in soil (Li et al., 2019). Finally, a study on the use of PLA composites in the production of disposable nonwovens, found that PLA blended with soy fillers can reduce production costs and increase biodegradability in a basic medium (Güzdemir, Bermudez, Kanhere, & Ogale, 2020).

Evidence gaps

While the biodegradability of many of the above products has been tested in laboratory-based soil or aqueous environments, few studies examined the potential impact of varied open environment conditions, or the fate of materials in these environments over longer timescales.

Considerations relating to open environments

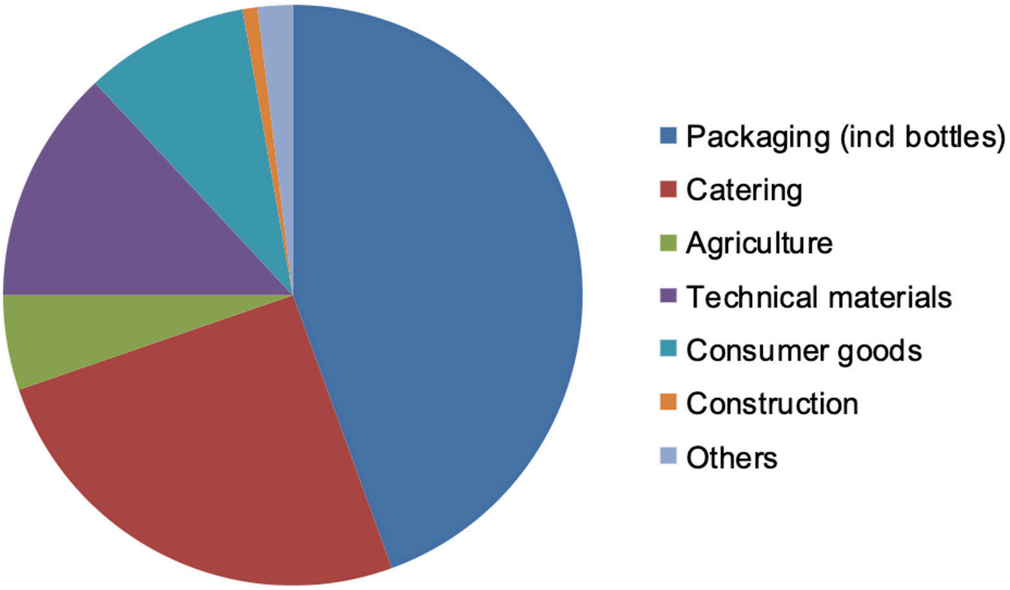
Other than agricultural mulch films and some building materials, which are specifically designed to biodegrade in the open environment, most of the biodegradable plastics in the above applications (with the exception of TPS and PHA) are only fully biodegradable under controlled composting conditions (e.g. (RameshKumar, 2020; Sikorska et al., 2019)). For example, PLA, the predominant material used as the basis for packaging applications, has limited biodegradability in open environments (Haider et al., 2019; Hong & Chen, 2017; Karamanlioglu et al., 2017), particularly in marine environments where a PLA bottle has been found to have a half-life of 58 years (Chamas et al., 2020). In landfill (not the open environment), PLA biodegradation, along with other organic waste, releases methane due to anaerobic conditions (RameshKumar, 2020; Rujnic-Sokele & Pilipovic, 2017; Sikorska et al., 2019). PLA has also been highlighted as holding potential to contaminate existing recycling processes if the quantities used increase, and does not fully biodegrade in anaerobic digesters used to convert organic waste into biogas (Quecholac-Pina et al., 2020; Rujnic-Sokele & Pilipovic, 2017). A growing, but currently limited area of research is focused on the development of chemically recyclable PLA (through de — and re-polymerisation or repurposing), in attempts to realise a 'circular economy solution' to PLA disposal (Beltrán et al., 2020; Hong & Chen, 2017; McKeown, Román-Ramírez, Bates, Wood, & Jones, 2019). Another niche development involves a PLA/PGLA blend, the latter increasing the biodegradability of PLA under anaerobic conditions, presenting a potential option for applications where waste separation is difficult (e.g. hospitals, stadiums), enabling PLA to enter mixed waste streams for anaerobic digestion (Samadi et al., 2019). However, currently the only broadly suitable end-of-life pathway for PLA is industrial composting (Quecholac-Pina et al., 2020).

Given that food packaging represents a significant proportion of commercial applications for biodegradable plastics, and considering the widespread use of PLA in the development of packaging materials, the above evidence highlights a critical role for consumer awareness, clear product labelling (including disposal criteria), and an efficient, enabling waste infrastructure with adequate composting facilities (Hong & Chen, 2017; RameshKumar, 2020; Rujnic-Sokele & Pilipovic, 2017). The current biodegradability certification labels in Europe — DIN Certo 'Seedling' and TÜV Austria 'OK Compostable' — indicate industrial compostability, not biodegradability in open environments, nor often compostability at home (Karamanlioglu & Alkan, 2019; Quecholac-Pina et al., 2020; Ruggero, Gori, & Lubello, 2019). The consequent consumer confusion surrounding end-of-life pathways for plastics defined as biodegradable means they are often incorrectly disposed of, resulting in unsuitable waste streams or the open environment (Hong & Chen, 2017; Karamanlioglu et al., 2017; Quecholac-Pina et al., 2020). As such, the research highlights how defining biodegradability in relation to different potential receiving environments is key — particularly differentiating between industrial/controlled and open environment biodegradability in product labelling, where what is excluded becomes as important as what is included (Quecholac-Pina et al., 2020). End-of-life management is emphasised as essential to realising the sustainability benefits of biodegradable plastics, and key challenges identified relate to certification and labelling, infrastructural development, and how these develop in the context of heterogeneous materials currently circulating at very low volumes (RameshKumar, 2020). Hann et al (Hann, 2020) highlight the uneven distribution of industrial composting facilities across the EU, as well as the considerable variability in their ability to treat 'compostable'/'biodegradable' materials (even those complying with the EN13432 standard).

Evidence gaps

The focus of the research throughout this section is again primarily directed towards the development of materials for specific applications and receiving environments, rather than examining the potential impact of diverse environmental conditions associated with a range of possible end-of-life scenarios. This gap is notable in research surrounding applications for which the fate of products is uncertain and difficult to control, such as food packaging. Further, given these uncertainties, and the evidence that many of the food packaging materials discussed above rely on specific (industrial) receiving environment conditions to be biodegradable, research on specific waste management strategies (such as labelling and waste infrastructure) is highlighted as lacking (Haider et al., 2019; Hong & Chen, 2017; Karamanlioglu et al., 2017; RameshKumar, 2020; Sikorska et al., 2019).

Figure 3. Illustration from Karamanlioglu et al., 2017



Global PLA application market in 2013 (Adapted from Occams Business Research & Consultancy).

Testing and certification (Chapter 4 of Evidence Review Report)

This section presents the evidence from 21 papers on the testing and certification relating to the biodegradability of plastics in the open environment.

Testing and certification of biodegradability	Number of papers
Biodegradability in controlled environments	4
Biodegradability in soil	9
Biodegradability in freshwater & wastewater	1
Biodegradability in marine environments	4
Ecotoxicology testing	4

Biodegradability in controlled environments

The majority of international standards, testing protocol and corresponding accredited third-party certification schemes for biodegradability relate to biodegradation in controlled environments (Quecholac-Pina et al., 2020; Ruggero et al., 2019). ASTM D5338 provides the main protocol for testing biodegradability under controlled composting conditions (ASTM International, 2021). However, there are a broad range of methodologies available and a synergistic approach, utilising several methods to enable cross-validation, is recommended to increase reliability (Ruggero et al., 2019). The two primary certification labels for biodegradable products in Europe are the DIN Certco 'Seedling' logo, and the TÜV Austria 'OK compost' logos, which demonstrate that a product meets the standard EN 13432 (European Union, 2000), indicating industrial compostability. This cannot be extrapolated to biodegradability in any open environments, including home compost. Certification explicitly pertaining to the latter, such as the TÜV Austria 'OK Compostable HOME' certification (TÜV Austria Green Marks), has no corresponding international standard, and is currently only utilised in Belgium.

Evidence gaps

Most biodegradable polymers are designed for controlled, aerobic composting, but evidence suggests that test protocols lack transferability to home composting conditions (Karamanlioglu & Alkan, 2019; Sikorska et al., 2019). Despite existing ISO and ASTM methods, there are no specifications for biodegradability in controlled anaerobic conditions such as landfill or anaerobic digesters (Quecholac-Pina et al., 2020).

Biodegradability in soil

Two international standards for the aerobic biodegradability of plastics in soil (ISO 17556:2012 and ASTM D5988-12) form the basis of the European standard for agricultural mulch film biodegradability, EN 17033:2018, and the associated TÜV Austria 'OK Biodegradable SOIL' certification (Briassoulis, Mistriotis, Mortier, & Tosin, 2020; Haider et al., 2019). Biodegradation tests pertaining to ASTM D 5988-12 are carried out in controlled laboratory conditions, at temperatures between 20 and 28 °C, to favour mesophilic organism growth (Pischedda, Tosin, & Degli-Innocenti, 2019). A study measuring CO2 evolution using the ASTM D 5988 method over one year at 20, 28 and 15°C, found that a thermal performance curve (mineralisation rates plotted against respective temperatures) perfectly reflected an exponential model, indicating the domination of thermodynamic effects within the 15-28°C range — significantly outside of that specified in the testing procedure (Pischedda et al., 2019). Sintim et al (Sintim et al., 2020) compared results from a laboratory-based study with results from mulch films in field conditions, across cool and warm temperatures, in both compost and soil, finding higher temperatures and compost to significantly increase biodegradation, and a significant lack of compatibility with laboratory results. However, when used to simulate landfill conditions in the State of Kuwait, the ASTM D 5988 method was found to produce reliable and repeatable results (Al-Salem, Al-Nasser, Sultan, Karam, & Iop, 2019).

A range of studies have highlighted both methodological limitations of current laboratory-based tests for plastic biodegradability in soil and have questioned their applicability to diverse open environment conditions. Alternatives have been proposed to overcome such limitations, for example, a quartering method using representative field samples to assesses the biodegradability of agricultural mulch films (and resultant polymer fragments) in soil (Ghimire et al., 2020). This was found to be effective over immediate and longer timescales (four years) and claims to be applicable across diverse field scenarios (Ghimire et al., 2020). Another study aimed to improve the reliability and reproducibility of results produced by current testing procedures (ISO 17556:2019/ASTM D5988, 2018) by removing a range of permitted methodological variations such as soil sample (can be natural or a laboratory mix), and test sample form (can be film, pulverised or other) (Briassoulis et al., 2020). Sander (Sander, 2019) proposed measures to overcome the limitations of laboratory-based tests, with attention to the three fundamental stages of mulch film biodegradation: colonisation of polymer, depolymerisation, and microbial assimilation. The limitations of current gravimetric analysis in assessing the non-mineralised fraction of biodegradable polymers in soil are highlighted, proposing solvent extraction methods, followed by nuclear magnetic resonance spectroscopy or gel permeation chromatography. Further, the inability of respirometric measurements of incubation systems to determine mass balance closure on polymer-derived carbon or its incorporation into soil biomass is identified as problematic, proposing the replacement of unlabelled polymers with carbon isotope-labelled polymers in soil incubations (Sander, 2019). Finally, as mentioned above, testing protocols that favour rapid biodegradation may impede the development of biodegradable polymers suitable for longer term use, as is often required for agricultural applications (Šerá et al., 2020). As a potential solution, accelerated soil biodegradation testing has been proposed, with increased incubation temperatures (Monami et al., 2019; Šerá et al., 2020).

Evidence gaps

The accelerated conditions of controlled laboratory testing for aerobic biodegradability in soil has been found to lack applicability to many open terrestrial environments, with respect to a range of variables including temperature, soil moisture content, pH levels, and microbial content (Haider et al., 2019). Different biodegradable polymers are favoured by different microorganisms, thriving under different pH, moisture and temperature conditions, and research shows that isolating polymers with specific microorganisms in optimal conditions does not simulate open environment conditions, where selected microorganisms may not be present, may not be predominant (and may therefore be outcompeted by others), or may prefer alternative substrates to the polymer as a carbon source (Haider et al., 2019). In-situ field testing has also been identified as potentially problematic and unreliable due to the variability of conditions over time and space, and challenges surrounding observation, measurement, and identifying locations representative of where waste is likely to result (Haider et al., 2019).

Biodegradability in freshwater and wastewater

The TÜV Austria 'OK Biodegradable WATER' certification, claiming to "guarantee biodegradation in a natural freshwater environment" is based on international standards for aerobic plastic biodegradation in waste water and sewage sludge (BS EN ISO 14851 (equivalent to BS EN 14048) and BS EN ISO 14852 (equivalent to BS EN 14047)) and anaerobic (BS ISO 13975 and BS EN ISO 14853). These standards also form the basis of the European standard EN 14987:2006 for plastic degradability in wastewater treatment plants (Harrison, Boardman, O'Callaghan, Delort, & Song, 2018).

Evidence gaps

There are currently no active standards for freshwater environments at international or regional level (Harrison et al., 2018). Testing protocols relating to the above wastewater standards have been highlighted as ill-suited to freshwater environments (Harrison et al., 2018): temperature ranges do not reach below 19°C, with upper limits extending to 63°C in some cases; six month maximum test durations are significantly shorter than evidence of plastic biodegradation in freshwater environments ((Harrison et al., 2018) citing Corcoran et al. 2015); static exposure fails to reflect flow-through likely in many unmanaged conditions; medium is artificially inoculated (except for BS ISO 13975); and recommended test material is powder form, evidenced to artificially increase biodegradation rates due to higher surface area ((Harrison et al., 2018) citing Yang et al 2005).

Biodegradability in marine environments

Two international standards relating to the biodegradability of plastics in the marine environment are currently active: ISO 18830:2016 for aerobic biodegradation in seawater and ISO 19679:2016 for biodegradability at the salt water-sediment interface (Harrison et al., 2018). Corresponding tests for CO2 evolution or oxygen demand (alongside two regional test methods ASTM D6691-09 and D7473-12) are all carried out under controlled laboratory conditions. The TÜV Austria 'OK Biodegradable MARINE' certification is based on ASTM D7081-05, a withdrawn specification, requiring 90% biodegradation rate after an exposure of six months duration (Harrison et al., 2018). Due to fragmented standards and testing procedures for marine biodegradability, the research finds considerable variability and inconsistency both between different testing protocols, as well as within particular methods, resulting in frequent false negative results for chemical persistence (Ott et al., 2020).

Alternative laboratory based tests have been developed, producing more reliable and less variable results for marine biodegradability by increasing sample sizes and bacterial cell concentrations in attempts to improve representation of microbial diversity, and extending time-periods beyond the 60 — day half-life threshold for the persistence of chemicals in seawater (Ott et al., 2020). Given the disparate protocol for assessing marine biodegradability, Chamas et al. (2020) have developed a metric in an attempt to harmonise measurements: the specific surface degradation rate (SSDR). SSDR extrapolates half-life values of different materials — found to be similar for PLA and HDPE, despite the former degrading significantly faster on land. Another study simulated four different water column compartments under aphotic and euphotic conditions, including both polluted and unpolluted sediment conditions, finding a significant diversity in PLA degradation rates (Beltrán-Sanahuja et al., 2020).

Evidence gaps

Harrison et al. (Harrison et al., 2018) and Weber et al. (Weber M, 2015) outline research demonstrating specific limitations to the reliability of testing protocol for the biodegradability of plastics in marine environments. These relate to inconsistencies both within and between methods, and the limited applicability of tests carried out in optimal laboratory conditions to the open environment:

- **Lack of specificity surrounding inoculate source and how it is prepared:** The use of preconditioned strains, static exposure, and synthetic media were all found to influence biodegradability rates, as well as inconsistencies between methods relating to strain selection and exposure ((Harrison et al., 2018) citing Yang et al 2004; Muller 2005), and variations in preparation methods such as filtration, storage time and cell density ((Harrison et al., 2018) citing Krzan et al 2006; Goodhead et al 2014).
- **Lack of specific test material guidelines:** Tests were not found to adequately account for the impact of polymer type or additives on biodegradation rates, or of the shape, size or surface properties of a material, where higher surface area (e.g. powders) and roughness can artificially increase biodegradation rate ((Harrison et al., 2018) citing Yang et al. 2005; Lucas et al. 2008; Jayasekara et al. 2005; Lo Re et al 2013). Film is generally the recommended test material, meaning results are unlikely to reflect the biodegradability of thicker plastics such as bottles.
- **Lack of applicability to unmanaged environments:** Marked absence of tests applicable to unmanaged environments, with laboratory-based procedures found to provide poor simulations of the open environment. Tests fail to capture the complexity of realistic exposure scenarios (e.g. flow-through conditions), or microbial taxa diversity and concentration ((Harrison et al., 2018) citing Goodhead et al 2014). Temperature is not representative of colder marine environments, with most test ranges limited to 13-30˚C, failing to account for regional and seasonal variation, and the influence of temperature on both taxonomic composition and microbial

communities' metabolic rates ((Harrison et al., 2018) et al 2018 citing Muller 2005). Finally, plastic biodegradation in aquatic environments is evidenced to be significantly longer in many scenarios (often decades) than the six-month maximal duration of most testing procedures ((Harrison et al., 2018) citing Corcoran et al 2015).

No robust procedure exists for the application of current marine biodegradability test scenarios to unmanaged conditions — a challenge compounded by the absence of research into plastic 'biodegradation' in open marine environments (Harrison et al., 2018). Further, besides ISO 19679:2016 there are currently no specific standards for salt marshes, deep sea zones or anaerobic marine environments (Harrison et al., 2018).

Ecotoxicology testing

There are significant evidence gaps in this area. Most standards, testing and certification schemes relating to biodegradability in both terrestrial and aquatic environments do not currently address how biodegradation products impact broader ecosystem functioning and biota (Haider et al., 2019; Harrison et al., 2018; Yin & Yang, 2020).

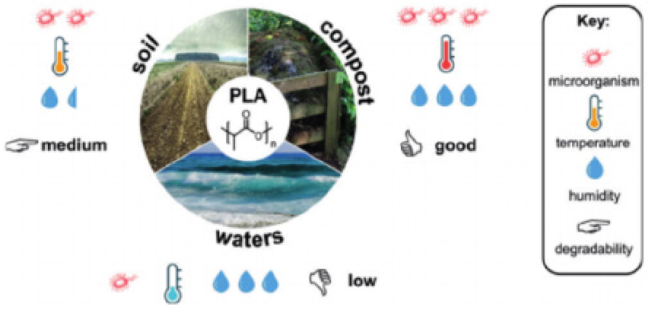
Aquatic environments

The only ecotoxicity tests relating to plastic biodegradation in aquatic environments are those forming part of the TÜV Austria 'OK Biodegradable MARINE' certification, yet one is a withdrawn specification, and one relates to a genus of crustacean that lives in freshwater (Harrison et al 2018). These tests also function on a species level, failing to address impacts on species communities and on biogeochemical processes ((Harrison et al., 2018) citing Green et al 2016). Further, bio-based polymer microbes (not accounted for in TÜV Austria toxicity tests), have been found to impact the feeding behaviour of species such as lugworm (Harrison et al., 2018).

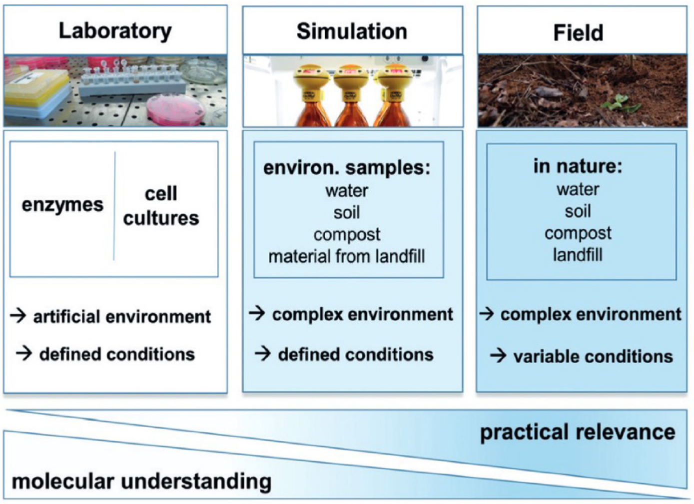
Terrestrial environments

Some ecotoxicity requirements have been established for compostability standards (EN 13432 requires plant germination and growth data), and proposed for soil biodegradability (ISO 17556:2019 incorporating toxicity tests for microorganisms, plants and earthworms) (Haider et al., 2019; Ruggero et al., 2019). However, polymer impact assessment is not covered by the European REACH legislation for chemicals' environmental impact, hence a significant lack of standards, research and data surrounding biodegradable plastic toxicology (Haider et al., 2019; Ruggero et al., 2019). Haider et al. (Haider et al., 2019) list ecotoxicity studies from a small body of research carried out on biodegradable plastics such as PLA, PBAT, PBS and starch blends used on agricultural mulch films. Potential temporary negative impacts on plants and microorganisms were identified relating to greater microbial activity and subsequent increased oxygen demand and fall in pH. However, most studies detected no lasting harmful impact, with the exception of PLA biodegradation, which was found to cause genotoxic and cytotoxic effects on onion plants (Allium cepa) ((Haider et al., 2019) citing Souza et al. 2019), and inhibition of microbial activity after an incubation period of 84 days ((Haider et al., 2019) citing Adhikari et al. 2016). However, sufficient evidence of ecotoxicology is said to require repeated, long-term investigation ((Haider et al., 2019) citing Fritz et al. 2003).

Figure 4. Illustrations from Haider et al., 2019.



Influence of humidity, temperature and concentration of (suitable) microorganisms on the biodegradation of PLA in different environments.



Comparison of different biodegradation tests for plastics.

Testing and certifying biodegradability in the open environment

In sum, the research highlights significant limitations relating to the current testing and certification of plastic biodegradability in open environments. This relates to fragmented standards, inconsistent test methodologies, and the challenges surrounding protocol that either simulate the open environment to a reasonable degree, or that can be carried out in the environment itself (and that take into account broader, short and long term toxicology impacts on ecosystems and biota) (e.g. Haider et al., 2019; Harrison et al., 2018). Current testing protocols for biodegradability in terrestrial and aquatic environments remain laboratory-based, under optimal conditions. The research concludes that using these tests in combination with in-situ, open environment testing is likely to provide the most accurate results (Haider et al., 2019; Harrison et al., 2018; Ott et al., 2020; Pischedda et al., 2019). However, it cautions that standard creation can lead to the false impression that the process and safety of biodegradability in open environments is fully understood (Haider et al., 2019; Harrison et al., 2018).

Ecological and other risk assessments (Chapter 5 of the Evidence Review Report)

The widespread use of plastics has resulted in degradation of the environment and economic costs for society. The disposal problems are related to slow degradation rates and resistance to microbial degradation, which lead to damaging accumulation (Sintim, Bary, et al., 2019).

In this context, the substitution of conventional plastics with biodegradable plastics has been increasingly accepted as a strategy to tackle plastic accumulation in the environment (Balestri et al., 2019; Chen, Wang, Sun, Peng, & Xiao, 2020; Haider et al., 2019). As a result, increasing attention has been given to developing biodegradable plastics derived from renewable resources (Emadian et al., 2017).

This section presents evidence on the ecological risks and other assessments relating to the introduction and presence of biodegradable plastics in the open environment.

Ecological impact evidence

A substantial share of the included publications address the degradation of mulch films and plastic bags, their impact on composting, soil health and microbial communities.

For instance, Bandopadhyay et al. (Bandopadhyay, Martin-Closas, Pelacho, & DeBruyn, 2018) undertook a review summarising literature on the impacts of plastic mulches on soil biological and biogeochemical processes, with a special emphasis on biodegradable plastic mulches. The combined evidence showed that, when used as a surface barrier, plastic mulches altered soil microbial community composition and functioning via microclimate modification. The incorporation into soil could also result in enhanced microbial activity and enrichment of fungal taxa.

Chen et al. (Chen et al., 2020) investigated the effects of biodegradable PLA microplastics (MPs) on soil microbiota and related ecological processes under condition of high or low carbon content. They found that PLA MPs had no significant effect on the overall diversity and composition of bacterial communities or related ecosystem functions and processes. However, there was an impact on the interactions between constituent species, which might have a legacy effect on soil bacterial communities and functions.

Results

A study concerning the impact of biodegradable seedling trays (BSTs) on the microbial communities was conducted by Meng et al. (2019). It showed that soil quality was not substantially affected by the use of BSTs. Even so, the microbial community was affected in a soil-dependent and time-dependent pattern. Community level profiling showed that BSTs significantly increased microbial activity and decreased functional diversity for a period of time. The impact had disappeared by the end of the period under analysis.

Sintim et al. (Sintim, Bandopadhyay, et al., 2019) found poor correlations and high spatial variations after studying the impact of four biodegradable plastic mulches on soil health at two sites. Soil health was first assessed in May 2015, and then every six months until May 2017, by measuring 19 soil properties (physical, chemical, and biological). The analysis showed that soil properties, social health indicators, and soil functions were affected more by site and time than by the mulch treatments.

Markowicz and Szymanska-Pulikowska (Markowicz & Szymanska-Pulikowska, 2019) highlighted that composting municipal organic waste results in a value product in the form of compost, which could be used instead of other forms of fertilisation. However, they note that this waste may contain oxo-biodegradable and biodegradable plastics which are used for waste collection. The analysis conducted on selected macro — and microelements in new and composed plastics (some of which are in-scope for this review) shows the occurrence of multidirectional changes in the content of those elements during composting, which may be the source of contamination of the fertiliser produced.

Similarly, Sintim et al. (Sintim, Bary, et al., 2019) assessed the degradation of biodegradable plastic during 18-week composting and determined whether additives from the plastics were released upon degradation. Plastic films containing PBAT and PLA/PHA were placed into meshbags and buried in compost. The results showed 99% macroscopic degradation of PLA/PHA and 97% for PBAT film. Polymers in the biodegradable films degraded. However, micro — and nanoparticles, most likely carbon black, were observed on the meshbags.

On the other hand, Deng et al. (Deng, Meng, Yu, & Wang, 2019) show that using fully biodegradable mulch films in an arid region has a positive effect on biomass yields. Indeed, the annual maize biomass yield increased by 24.5%, 28.9% and 32.9% between 2015 and 2017. Furthermore, by using future climate confitions, their work also suggests that degradable mulch films can increase water use efficiency by an average of 9.5%. Sander (Sander, 2019) argues that using biodegradable mulch films instead of conventional PE-based films promises to improve the sustainability of agricultural food production by overcoming adverse economic and ecological impacts resulting from the accumulation of remnant PE films in agricultural soils.

Impact on living organisms was subject to analysis by Ludevese-Pascual et al. (Ludevese-Pascual et al., 2019), which found that PHB-based artificial substratum enhances the survival of postlarval tiger shrimp and improves performance against adverse environmental conditions and disease resistance, when compared to PVC substratum.

Some other publications focused on matters such as the production of plastic products, their impact on the natural environment at large and on human health.

Bałdowska-Witos et al. (Bałdowska-Witos et al., 2020) carried out a Life Cycle Assessment (LCA) analysis to identify potential environmental burdens for the bottle forming process. It showed that, while the operation of stretching and lengthening of PLA preform into bottles is more environmentally friendly than similar processes conducted with PET preform, both types of bottles pose a real threat to the natural environment. The review conducted by Walker and Rothman (Walker & Rothman, 2020) also summarises the state-of-the-art in comparative Life Cycle Assessment of fossil-based and bio-based polymers and the significant current variation in methodologies employed.

Souza and Fernando (Souza & Fernando, 2016) focused on nanoparticles (NPs) that are applied to biodegradable plastic packaging as reinforcement to improve barrier and mechanical properties of polymers. Their review highlights studies that suggest the capacity for microbial degradation is kept but the speed may be different. Scarfato et al. (Scarfato, Di Maio, & Incarnato, 2015) looked at the state-of-the-art of PLA, starch and PHAs in terms of the limitations in processability and performance for food-contact uses, as well as the solutions found to overcome challenges – the main one being by mixing other polymers and/or adding other substances. The studies reviewed by the authors show that such solutions do not introduce unacceptable detrimental effects concerning packaging-food migration. Adeyeye (Adeyeye, 2019) also considered bio-based packaging a veritable alternative to conventional packaging.

Biodegradation rates were frequently highlighted by publications as an important element to take into account. Chamas et al. (Chamas et al., 2020) attempted to harmonise different measurements for biodegradation rates – via the specific surface degradation rate (SSDR) – and found that SSDRs for HDPE and PLA were similar in the marine environment, although PLA degrades approximately 20 times faster than HDPE on land.

The review conducted by Emadian et al. (Emadian et al., 2017) highlights findings attributed to the biodegradation of bioplastics in various environments, environmental conditions and degree of biodegradation. This was extensively studied in soil and compost environments, in which biodegradable plastics showed high degradability.

Risks relating to the presence of biodegradable plastics in the open environment

Several authors highlight the potential risks in allowing biodegradable plastics to remain in the open environment. For instance, Haider et al. (Haider et al., 2019) acknowledge that such plastics are not always as biodegradable as they claim to be.

Emadian et al. (Emadian et al., 2017) highlight that despite potential high degradability, a large amount of those plastics still find their way to the water bodies and to marine systems, affecting different species of plant and animals adversely. Haider et al. (Haider et al., 2019) argue that humidity, temperature or concentrations of microorganisms vary in different environments, resulting in different biodegradation rates.

Chen et al. (Chen et al., 2020) highlight evidence that shows biodegradable plastics can produce more microplastics, which have become a contaminant of increasing concern in soils. Markowicz and Szymanska-Pulikowska (Markowicz & Szymanska-Pulikowska, 2019) state that plastic used for organic waste collection may be a source of contamination for composting, an otherwise viable alternative to other fertilizers. Contaminants in the form of microplastics may also be released into and become a threat to the environment, including animals and humans. Bandopadhyay et al. (Bandopadhyay et al., 2018) suggest that despite the fact that total carbon input from biodegradable mulches is small, a stimulatory effect on microbial activity may ultimately affect soil organic matter dynamics.

Evidence gaps

Evidence is scarce and inconclusive and most recent research studies emphasise the existence of substantial gaps in evidence in relation to ecology and toxicity in the open environment and the need for further research (Emadian et al., 2017; Sintim, Bandopadhyay, et al., 2019) Souza and Fernando (Souza & Fernando, 2016) and Adeyeye et al. (Adeyeye, 2019) argue that nanoparticles have the theoretical potential to migrate to the packaged foodstuff, which is later consumed by humans. Scarfato et al. (Scarfato et al., 2015) highlight that reviewed studies on migration of substances between packaging and food cover food simulant solvents only.

Even though biodegradable plastics have been widely introduced into agricultural production, Meng et al. (Meng et al., 2019) argue that their impacts on the soil ecosystem (functions and processes, as well as microbial communities) remain unclear. Authors highlight that there are few studies on degradable mulch films and their impact on soil health (Chen et al., 2020; Deng et al., 2019; Sintim, Bandopadhyay, et al., 2019). Sander (Sander, 2019) acknowledges that the safe application of biodegradable mulch films – including their desired biodegradation in soils – requires that their fate in soils is well studied and understood at a mechanistic level.

Chamas et al. (Chamas et al., 2020) highlight the need for better experimental studies under well-defined reaction conditions, standardised reporting of rates, and methods to simulate polymer degradation. Sintim et al. (Sintim, Bandopadhyay, et al., 2019) call for assessment under long-term studies to better establish the effects on biodegradable plastic mulches on soil health. This is reaffirmed in Sintim et al. (Sintim, Bary, et al., 2019), which call for longer field testing to ensure that either complete biodegradation occurs or that no long-term harm to the environment is caused. Bandopadhyay et al. (Bandopadhyay et al., 2018) also argue for long term studies and a better understanding of impacts of biodegradable mulches on nutrient biogeochemistry.

Finally, the lack of LCA data is highlighted by Bałdowska-Witos et al. (Bałdowska-Witos et al., 2020). In the context of the production of plastic bottles, the authors call for improvement in the availability and reliability of LCA data, development of more detailed scenarios of environmental impacts and damages, provision of indicators for arising deficiencies in the production process and inclusion of economic analyses. Walker and Rothman (Walker & Rothman, 2020) also encountered great variations in the comparative study conducted on LCAs for fossil-based and bio-based polymers. Indeed, such results could come down to a variation in methodologies and standards. Results suggest that a large part of this variation is related to the Life Cycle Assessment methodologies applied, particularly in the end-of-life treatment, the use of credits for absorbed Carbon Dioxide, and the allocation of multifunctional process impacts. Even so, Haider et al. (Haider et al., 2019) claim that the development on new biodegradable plastics based on life cycle assessments to be inevitable going forward, as it is impossible to create a one-size-fits-all solution.

Considering the widespread use of plastic products and the growing attention given to biodegradable plastics, it becomes important that knowledge gaps are bridged, and answers are provided, alongside proper legislation (Souza & Fernando, 2016).

Social and behavioural aspects (Chapter 6 of the Evidence Review Report)

This section presents evidence on social and behavioural aspects of plastic biodegradability. The majority of research in this area focuses on consumer awareness, attitudes and intentions relating to the purchase and disposal of biodegradable plastics, and the economic aspects of these transitions.

Social and behavioural aspects	Number of papers
Public understanding, perceptions and behaviour	13
Farmer perceptions of biodegradable plastics in agriculture	5
Retail and industry settings	6

Public understanding, perceptions and behaviour

Consumer attitudes and intentions

Several studies found that consumer attitudes towards biodegradable plastic were overwhelmingly positive due to its perceived sustainability, and many expressed a desire to see more of it used for consumer goods (Dilkes-Hoffman, Ashworth, Laycock, Pratt, & Lant, 2019; Klein, Emberger-Klein, Menrad, Möhring, & Blesin, 2019; Nguyen, 2020). These attitudes were shown to correspond to consumer intentions relating to purchase, and their willingness to pay (WTP) a premium for products made with (or grown using) biodegradable plastics in Germany (Ketelsen, 2020; Klein et al., 2019; Klein, Emberger-Klein, & Menrad, 2020), Yogyakarta (Harianja, Saragih, & Fauzi, 2019), China (Hao et al., 2019) and the USA (Chen, Marsh, Tozer, & Galinato, 2019). However, WTP was found to be moderated by income (Chen et al., 2019; Klein et al., 2019), and Norfaryanti et al (Norfaryanti, Sheriza, & Zaiton, 2019) found that a relatively small percentage (3.5%) preferred to buy 'environmentally-friendly packaging' in a Malaysian study. Prior environmentally-conscious purchasing behaviours and 'green' values were found to increase consumer intentions to buy biodegradable plastics or WTP more for them (Chen et al., 2019; Confente, Scarpi, & Russo, 2020; Klein et al., 2019; Klein et al., 2020; Russo, Confente, Scarpi, & Hazen, 2019). Some studies found that women were more likely to purchase biodegradable plastics (Chen et al., 2019; Kim & Jin, 2019), however, others found no gender-based variation (Russo et al., 2019). Another area identified in the research as significantly impacting purchase intentions or WTP was product performance, such as convenience, durability/quality and reusability (Hao et al., 2019; Harianja et al., 2019; Ketelsen, 2020) and effective marketing (Kim & Jin, 2019; Nguyen, 2020).

Consumer awareness

While the research identifies positive consumer attitudes towards biodegradable plastics and, to varying degrees, a WTP a premium for them, it highlights considerable consumer confusion relating to both what biodegradable plastics are, and how they should be disposed of correctly (Boesen, Bey, & Niero, 2019; Dilkes-Hoffman, Ashworth, et al., 2019; Hao et al., 2019; Ketelsen, 2020; Neves, 2020; Nguyen, 2020). Consumers were found to conflate the term biodegradability with compostability, as well as characteristics such as being recyclable, bio-based, or environmentally friendly more broadly (Dilkes-Hoffman, Ashworth, et al., 2019). Research comparing LCAs of beverage containers and consumer perceptions of their environmental impact found significant discrepancies between them (Boesen et al., 2019).

Consumer behaviours

The research on actual/real-world consumer behaviours relating to the purchase and disposal of biodegradable plastics is much more limited and indicates that these behaviours often do not correspond to the consumer attitudes and intentions outlined above. For example, purchase behaviours are found to be limited by price, conflicting with purported WTP (Ketelsen, 2020) and, while perceived positively due to environmental benefits, biodegradable plastics are often disposed of incorrectly, despite information communicated by packaging labels (Taufik et al., 2020). Familiarity with 'bio-based' products was found to mitigate this for compostable products; however, these were still more likely to be incorrectly disposed of than fossil-based packaging (Taufik et al., 2020). Consumer confusion (and frustration) surrounding a proliferation of 'eco-labels', and their unclear implications for waste separation were found to hinder both the correct disposal, and the initial purchase of biodegradable plastics (Ketelsen, 2020; Neves, 2020). Boz et al. (Boz, 2020) found that an overwhelming majority of participants in a study using eye-tracking technology did not look at sustainability ratings logos. A lack of certification on labelling apparel was also found to provide a negative utility for consumers (Klein et al., 2020), with questions around trust and consumer deception raised by research identifying false biodegradability claims, including carrier bags (Nazareth et al., 2019).[4] Finally, the presence of an enabling and efficient waste infrastructure is highlighted as a key determinant of effective disposal behaviour (Rujnic-Sokele & Pilipovic, 2017).

Evidence gaps

The majority of consumer-focused research looked at attitudes (and behaviours, to a lesser extent) relating to the purchase of biodegradable plastics. Research on consumer awareness and behaviour relating to disposal was limited — a notable evidence gap, given the necessity that biodegradable plastics result in the correct/desired receiving environment in order for their benefits to be realised.

Farmer perceptions of biodegradable plastics in agriculture

Price premiums associated with biodegradable plastics were found to be prohibiting their uptake in agriculture, with research concluding that a government role will be important in making biodegradable plastic mulch films a financially viable alternative to polyethylene (PE), in light of both price sensitivity, and poorly understood broader economic risks. For example, pumpkin growers in Tennessee using biodegradable films experienced economic impacts relating not only to direct film costs, but to mulch adhesion, which was found to lower pumpkin price by up to 5% (Velandia, Wszelaki & Suzette 2019). Adhesion impact on price is poorly understood and researched, and known

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[4] This issue has also been raised by Napper and Thompson (2019) (cited in SAPEA 2020) although the composition of the bags was not analysed so not possible to know if this paper meets the inclusion criteria for this mapping review. Napper, I. E. and Thompson, R. C. (2019) 'Environmental Deterioration of Biodegradable, Oxo-biodegradable, Compostable, and Conventional Plastic Carrier Bags in the Sea, Soil, and Open-Air over a 3-Year Period', Environmental Science and Technology, 53(9), pp. 4775–4783. doi: http://dx.doi.org/10.1021/acs.est.8b06984

to be subject to a range of procedural and geographical variables (Velandia, Wszelaki & Suzette 2019). Most biodegradable films were not proven to be financially viable alternatives to PE films in open air pepper production in Spain, with current subsidy levels failing to cover additional costs (Mari et al. 2019). While there are regional variations in both uptake and interest (Goldberger et al. 2019), few fruit and vegetable growers in EU and US contexts were found to have used biodegradable mulch films, or to be prepared to in future without financial incentives (Marí, Pardo, Cirujeda, & Martínez, 2019; Velandia, DeLong, Wszelaki, Schexnayder, Clark & Jensen 2020; Velandia, Wszelaki & Suzette, 2019).

Evidence gaps

While financial incentives were highlighted as necessary in promoting the use of biodegradable mulch films, no research explored the feasibility or potential impact of possible mechanisms. Research also highlighted a lack of evidence relating to potential unknown and longer-term economic impacts of transitioning to biodegradable mulch films, such as mulch adhesion (Velandia, Wszelaki & Suzette, 2019).

Retail and industry settings

In relation to the uptake of biodegradable plastics in trade and retail, the research finds that the costs of transitioning from fossil-based plastics outweigh the benefits of adopting more sustainable alternatives. Using biodegradable or 'bio-based' plastics as part of Corporate Social Responsibility schemes or a shift towards 'circular business models', is demonstrated as a means to gain competitive advantage through 'eco-credentials' (Lim & Arumugam, 2019; Salvador, 2020). However, research relating to 'bio-based' plastics in general highlights significant economic barriers relating to higher direct costs, as well as costs relating to altering supply chains and gaining customer 'buy-in' hampering market penetration (Dijkstra, van Beukering & Brouwer, 2020; Friedrich, 2020). The research highlights a need for government financial mechanisms, and found support for a Pigovian tax on fossil fuel-based plastic packaging as a means to increase the uptake of 'bio-based packaging, with packaging weight favoured as a taxation basis, and labelling to indicate carbon emissions.

At a production level, research has also identified cost as a limiting factor, with many consumers unwilling to pay higher prices for biodegradable plastics, and limited scope for production at scale (Yadav & Pandey, 2020; Yin & Yang, 2020). Cost is found to pose particular barriers to the development and scaling of newer bio-based polymers such as edible food packaging, limiting production to laboratory scale, alongside other factors such as health and safety, technical processing issues and consumer awareness and acceptance (Jeya Jeevahan et al., 2020). Even for more widely produced biodegradable polymers such as PLA and PHA, production is largely confined to niche markets (Yadav & Pandey, 2020; Yin & Yang, 2020). Challenges relating to the high costs of PHA substrates have led to increasing interest in the use of waste/surplus materials as feedstock, however improvements in waste infrastructures (relating to both inputs and outputs of the production process) are highlighted as important in advancing efficiency and circularity in this industry (Yadav & Pandey, 2020; Yin & Yang, 2020). Food and agricultural waste valorisation has been found to provide economic advantages over the production of fossil-based plastics, including lowering production costs, the creation of new employment opportunities, and avoiding negative externalities relating to the impact of first generation feedstock on food prices (Yadav B & Pandey, 2020). Fahim et al. (Fahim, Chbib, & Mahmoud, 2019) demonstrate the economic feasibility of PLA pellets made from food and agricultural waste (from coffee and cotton respectively), identifying potential direct economic benefits relating to production costs, and indirect benefits through job creation. Finally, in a LCA on PLA feedstock, Bussa et al. (Bussa et al., 2019) found that replacing maize with cyanobacteria was not a sustainable option, due to high carbon-dioxide and electricity requirements. However, the research suggested upscaling production and utilising wind power for energy as potential means to considerably reduce environmental impact, and further research opportunities were identified in the utilisation of biomass residues.

Evidence gaps

The research primarily focused on the production and uptake of biodegradable plastics in retail and industry, rather than end of life pathways/management.

Policy-related research (Chapter 7 of the Evidence Review Report)

This section presents the evidence on policy relating to biodegradable plastics. Little research was identified in this area, limited to studies examining the social, economic and environmental impacts of market-based policies and studies on broader waste management regulation, primarily focused on the impact of single use plastic bans/taxes on consumer and industry behaviours relating to biodegradable alternatives.

Four studies were included that examined the intersection of biodegradable plastics and waste regulation. Briassoulis et al. (Briassoulis, Pikasi, & Hiskakis, 2019) reviewed an inventory of end-of-use options for bio-based products developed from EU environmental legislation, identifying optimal pathways on the basis of impact on the environment and conventional waste streams. Other studies focused explicitly on single-use plastic (SUP) bans or taxation implemented by various governments, and their implications for the use of biodegradable plastics. While these are not currently exempt from SUP regulation due to difficulties in determining the relative biodegradability of different materials (Harrison et al., 2018), taxes and bans have raised awareness of the impact of plastic waste, driving consumers towards alternatives perceived as more sustainable (Pacatang, 2020). Market response to SUP regulation has involved the emergence of new products (e.g. bags, straws) claiming biodegradability, while evidence highlights false claims and 'greenwashing' due to a lack of clear regulation and standards (Viera, Marques, Nazareth, Jimenez, & Castro, 2020).

Evidence gaps

No in-scope studies examined the extent or impact of the emergence of new products (and their potentially misleading labelling, e.g. Viera et al. (Viera et al., 2020)) in response to SUP regulation. No recent research was identified relating to market-based policies.

Summary of findings

The evidence presented in this report provides a brief summary of recent research evidence relating to a number of plastics that were initially considered as potentially biodegradable (see Appendix 1).

The research findings relating to the rate and extent of breakdown of each of these plastics emphasise the importance of the conditions (the receiving environment) that the material is exposed to both during and after its intended use.

This systematic mapping review presents a broad picture of recent research on each of the included plastics since studies in laboratory and home composting, as well as open environment settings are covered. Findings are mapped to the chapters from the extensive Evidence Review Report (SAPEA, 2020) to which this review is linked. Summary points, based on the evidence reviewed under each of the topics considered, are given below.

Biodegradable plastics as materials and the open environment

- Some types of thermoplastic starch biodegrade in some open environments (e.g. soil and home compost) but attempts to address poor mechanical properties through processing and blending may reduce biodegradability (p.12).
- Polyactides (PLA) have desirable mechanical properties but limited biodegradability in the open environment. Additives/composites may improve their biodegradability under controlled conditions (p.14).
- PLA degrading microorganisms have been identified and isolated that enhance biodegradation under controlled conditions (p.16).
- Polyhydroxyalkanoates (PHA) biodegrade under a relatively wide range of conditions (including open environments) and have good mechanical properties. High production costs can be significantly reduced with the use of waste products as feedstock (p.17).
- A small number of studies have focused on the biodegradation of other biodegradable plastics under controlled conditions (p.19).
- Much of the recent research has examined biodegradability in **controlled laboratory environments** and there is a significant lack of research relating to the **open environment** (particularly in specific environments, such as aquatic, for example). Yet specific environmental conditions are known to be highly influential and it is difficult to extrapolate results achieved under idealised laboratory conditions. The SAPEA

Evidence Review Report uses the term 'system property' to describe the combination of material and environment in assessing the biodegradability of plastics in the open environment (p.19).

Applications of biodegradable plastics

- There is good evidence to suggest that overall crop yields, fruit quality and soil ecology measures from biodegradable mulch materials are similar, or better than, those from the non-biodegradable polyethylene in a range of contexts, despite film degradation typically being underway within several months of transplant (p.21).
- Short timescales associated with the testing protocol for mulch film biodegradability may hinder development of suitable materials. There is a lack of evidence on the longer-term impacts of biodegradable plastics such as mulch films if they persist (p.22).
- PLA-starch composites are currently considered an attractive option as packaging materials since their combination addresses some of the limitations of the individual components. However, materials are designed for industrial composting and evidence of biodegradability in the open environment is limited (p.27).
- Other recent research studies have explored PHA composites as building materials (p.24); edible thermoplastic starch films (p.25); PLA cosmetic microbeads (p.25); various plastics for carrier bags (p.26) and cosmetic packaging (p.29); and PLA blends for fabrics (p.30).
- Due to the ambiguity surrounding end-of-life pathways for plastics defined as biodegradable, they may be incorrectly disposed of, within unsuitable waste streams or end up in the open environment (p.30).
- There is a lack of studies on specific applications, such as fireworks, dolly rope and fruit/veg stickers.

Testing and certification

- Controlled laboratory testing for biodegradability lacks applicability to many open environmental conditions (p.33).
- Current open environment certification schemes for soil, water and marine environments are based on inappropriate standards and testing procedures and using laboratory tests in combination with in-situ open environment testing is likely to provide the most accurate results (p.33).
- A number of recent research studies have proposed methods to overcome the limitations of laboratory testing for soil and compost environments (p.33).

- There are significant evidence gaps in current ecotoxicology testing procedures (p.37).
- Overall, there is a either a lack of evidence, or insufficient rigour, when it comes to testing standards and protocols for some specific open environments.

Ecological and other risk assessments

- Degree and speed of biodegradation are often regarded as key elements in assessing risks for use of biodegradable plastics in the open environment (p.39).
- Most recent studies focus on the impact of polymers on soil health, its ecosystems and microbial communities and suggest some benefits from use of biodegradable plastics [3.5.1] but also risks of incomplete degradation and residual microplastics, and from additives such as nanoparticles (p.42).
- Gaps in knowledge are widely recognised, particularly when it comes to long-term studies in real conditions and the actual impact of biodegradable plastics. Overall, there are substantial gaps in evidence of the impact on ecology and the risks of toxicity (p.42).

Social and behavioural aspects

- Public attitudes towards biodegradable plastic are overwhelmingly positive and, to varying degrees, associated with 'willingness to pay' (p.44).
- Consumers are unclear on terminology around biodegradable plastics and appropriate disposal criteria (p.44).
- In agricultural settings, the costs of transitioning from fossil-based plastics tend to outweigh the benefits of adopting biodegradable alternatives (p.45).
- In retail and industrial settings, the costs of transitioning from fossil-based plastics tend to outweigh the benefits of adopting biodegradable alternatives, although there can be some economic benefits (p.46).

Policy-related research

- There is very little recent policy related research, including market=based policies. Four recent studies have examined the intersection between biodegradable plastic use and waste regulation and its positive effects on consumers but mixed effects on market response (p.47).

Limitations of the review

This was a rapid mapping review to give an overview of current published evidence in the field. It is based on information extracted from comprehensive literature reviews (published since 2015) and content, primarily from abstracts, of recent primary studies (published 2019 to 2020) to bring the evidence base up to date. Thus, whilst this is an important body of literature based on a systematic search for peer reviewed research publications, the analysis maps the coverage of this body of evidence rather than providing a detailed data extraction and critical analysis of each included study.

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Annex 1. Inclusion/exclusion criteria

Population	Global
Include	Include research on biodegradable plastics with relevance to the open environment 'Biodegradable' polymers initially considered by the Working Group: Polyethylene succinate (PES), polybutylene succinate (PBS), poly(butylene succinate-co-butylene adipate) (PBSA), polybutylene adipate terephthalate (PBAT), polycaprolactone (PCL), all polylactides (PLA), polyhydroxyalkanoates (PHA), thermoplastic starches, cellulose acetate
Types of study	All relevant published evidence from the peer-reviewed and grey literature if it comprised a comprehensive review published since 2015 or a research study published since 2019 which had not yet been summarised within a review. All languages where the English language abstract described the research findings.
Exclude	Specific biomedical and bioengineering applications and lab-based studies that don't relate to applications for, or biodegradation in, the open environment. Out of scope 'biodegradable polymers' (e.g. polyhydroxybutyrate (PHB), chitosan) and composites comprising in and out-of-scope polymers (or other additives) unless the research study is describing improved degradation rates in comparison to 'in-scope' single or composite polymers.

Annex 2. Search strategy

Electronic sources (databases and websites)

Languages

- English and all other European languages

Dates

- From 2015 to 2020 for reviews
- From Jan 2019 to June 2020 for primary studies

Databases

- Scopus — and its citation tracking database SciVal
- Web of Science

Websites

- European Commission European websites: circular economy and waste.
- PLA-NET The Plastic Network

Supplementary searching

- Citation/reference list tracking of published research by the authors publishing two or more papers on different studies in 2019-2020 (10 authors in all) and these authors were also contacted to ask about recent studies, specifically those in the grey literature (which would not have been indexed in the databases searched) and 'in press' studies.
- Inclusion of publications (meeting inclusion criteria for the mapping review) from the individual searches carried out for and by members of the Working Group.

Search strategy

The strategy for Scopus is listed below. Database searching was carried out on 14 May 2020 and supplementary searching was completed by 19 June 2020.

CHAPTERS 2–5 & 7 OF THE ERR

TITLE-ABS-KEY(((plastic* OR polymer*) AND (biodegrada* OR compostable OR bioremediation OR degradab*)) OR bioplastic* OR "bio-plastic" OR "biobased plastic*" OR "bio-based plastic*" OR "biopolymer" OR "bio-polymer" OR plastisphere OR "polyethylene succinate" OR "polybutylene succinate" OR "poly(butylene succinate-cobutylene adipate" OR PBSA OR "polybutylene adipate terephthalate" OR PBAT OR polycaprolactone OR PCL OR polylactide* OR PLA OR PLLA OR PDLA OR PLAX OR "polylactic acid" OR polyhydroxyalkanoate* OR "polyhydroxy alkanoate*"OR PHA OR "thermoplastic starch*" OR TPS OR "cellulose acetate")

AND

TITLE-ABS-KEY(compost* OR soil* OR water* OR land* OR river* OR ocean OR sea* OR marine OR environment* OR agricultur* OR runoff OR mulch* OR "ecolog*" OR waste OR "circular econom*" OR microb* OR bacteria* OR microorg* OR micro-org* OR fung* OR takeaway OR food* OR package* OR litter* OR bag* OR sediment*)

AND

TITLE-ABS-KEY (((environment* OR eco* OR field OR biodegrad* OR degra* OR persisten* or dissipat* OR breakdown OR minerali?ation OR disintegration) W/5 (condition* OR criteri* OR factor* OR characteristic* OR value* OR advantage* OR consequence* OR disadvantage* OR risk* OR hazard* OR exposure* OR toxicol* OR polic* OR guideline* OR regulation*)) OR ecotoxi* OR ((biodegrad* OR degra* OR persisten* or dissipat* OR breakdown OR minerali?ation OR disintegration OR CO2) W/5 (rate* OR test* OR certification* OR ISO OR ASTM OR "3-tier system" OR "three-tier system" OR standard*)))

Limited to Reviews 2015–2020 Chapters 2–5 & 7: **400 hits**

Limited to 2019–2020 (all studies excluding reviews) Chapters 2–5 & 7: **1763 hits**

CHAPTER 6 OF THE ERR

TITLE-ABS-KEY(((plastic* OR polymer*) AND (biodegrada* OR compostable OR bioremediation OR degradab*)) OR bioplastic* OR "bio-plastic" OR "biobased plastic*" OR "bio-based plastic*" OR "biopolymer" OR "bio-polymer" OR plastisphere OR "polyethylene succinate" OR "polybutylene succinate" OR "poly(butylene succinate-cobutylene adipate" OR PBSA OR "polybutylene adipate terephthalate" OR PBAT OR polycaprolactone OR PCL OR polylactide* OR PLA OR PLLA OR PDLA OR PLAX OR "polylactic acid" OR polyhydroxyalkanoate* OR PHA OR "thermoplastic starch*" OR TPS OR "cellulose acetate")

AND

TITLE-ABS-KEY ((consumer* OR customer* OR public* OR human* OR takeaway OR food* OR package* OR litter* OR bag*) W/5 (respons* OR attitude* OR experienc* OR behav* OR understand* OR knowledge* OR perce* OR decision* OR label* OR communication* OR economic* OR cost* OR moneti*))

Limited to Reviews 2015–2020 Chapter 6: **39 hits**

Limited to 2019–2020 (all studies excluding reviews) Chapters 2–5 & 7: **167 hits**

Annex 3: Acknowledgements

Review Team

- Dr Alison Weightman, Specialist Unit for Review Evidence (SURE), Cardiff University
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Annex 4: Glossary of definitions

(adapted from SAPEA, 2020)

Additives: Organic and inorganic compounds and substances mixed into or applied to the surface of plastics to bestow desired material properties on the plastic. These additives are diverse and include, but are not limited to, antioxidants, binders, colourants, flame retardants, inhibitors, plasticisers, reinforcements, and stabilisers

Biodegradable plastic: A plastic that undergoes biodegradation involving the metabolic utilisation of the plastic carbon by microorganisms such as bacteria, fungi, and algae resulting in the conversion of plastic carbon to CO_2 (and CH_4) and microbial biomass

Biopolymer: A polymer produced by a living organism.

Blend: A mix of two or more polymers to get a single phase as opposed to a composite which is a multiphase, multicomponent systems

Composite: A material consisting of two or more distinct components (fillers or reinforcing materials) in a compatible binding matrix. When at least one of the distinct immiscible components is a polymer, the material is called as polymer composite [ASTM D883-20a].

Degradable plastic: A plastic or matrix which can degrade under certain environmental conditions in specific time period, resulting in loss of properties as measured by standard test methods. Degradation of plastic can result either from hydrolysis (hydrolytic degradation), oxidation (oxidative degradation) and due to light (photo degradation) or a combination of these effects [ASTM D883-20a].

Degradation: Chemical changes in a polymeric material that usually result in undesirable changes in the in-use properties of the material.

Fibre: A homogeneous strand of a material with finite length which is an order of magnitude larger than the diameter of the fibre. Fibres can be of natural origin or synthetically generated by drawing from a bulk material.

Glass transition: A reversible change in an amorphous polymer or in amorphous regions of a partially crystalline polymer, occurring while transitioning either from or to a viscous or rubbery state from or to a hard and relatively brittle state. The temperature at which this transition takes place is referred to as glass transition temperature (Tg) [3, ASTM D883-20a].

Macromolecule(s): A molecule of high relative molecular mass, the structure of which essentially comprises the multiple repetition of units derived, actually or conceptually, from molecules of low relative molecular mass.

Mineralisation: The conversion of and organic substrate (including biodegradable plastics) into the gases CO_2 (and CH_4), water, inorganic salts. mineralisation involves metabolic activity of microorganisms.

Monomer: A small molecule which is capable of reacting with either like or unlike molecules via chemical linkages to form long chain macromolecules.

Oligomer: A substance originating from repetitive linkage of a monomer to like molecules. Based on number of repetitive monomeric units linked oligomers are often referred to as dimers (two monomer units), trimers (three), and tetramers (four). This conversion process is called as oligomerisation [ASTM D883-20a].

Open environment: All natural (eco)systems including terrestrial environments (e.g., soils), riverine and lacustrine freshwater environments, as well as marine environments (e.g., estuaries and oceans). The term includes human-impacted ecosystems, such as agro-environments, but does not include manmade managed systems such as industrial and domestic composts.

Plastic(s): A material that contains as an essential ingredient one or more organic polymeric substances of large molecular weight. It is solid in its finished form but can be shaped by flow during manufacturing or finishing into finished articles [ASTM D883-20a].

Plastic biodegradation: The microbial conversion of all organic constituents in plastic to carbon dioxide, new microbial biomass and mineral salts under oxic conditions, or to carbon dioxide, methane, new microbial biomass and mineral salts under anoxic conditions. See chapter 2 for full discussion.

Polymer(s), Polymeric: Defined by IUPAC as 'a substrate composed of macromolecules' and furthermore macromolecules as 'a molecule of high relative molecular mass, the structure of which essentially comprises the multiple repetition units derived, actually or conceptually, from molecules of low relative molecular mass'.

Toxicity: A measure of adverse effects exerted by a chemical agent on a living organism or a biochemical process under specific environmental conditions and concentrations.

Annex 5: Abbreviations

DSC	Differential scanning calorimetry
EPR	Electron Paramagnetic Resonance spectroscopy
ERR	Evidence Review Report (SAPEA 2020)
FTIR	Fourier-transform infrared spectroscopy
LCA	Life cycle assessment
MCC	Microcrystalline cellulose
NFC	Nanofibrillated cellulose
PBAT	Polybutylene adipate terephthalate
PBS	Polybutylene succinate
PBSA	Poly(butylene succinate-co-butylene adipate)
PCL	Polycaprolactone
PE	Polyethylene
PES	Polyethylene succinate
PHA	Polyhydroxyalkanoate(s)
PLA	Polytactide(s)
PP	Polypropylene
SUP	Single use plastic
TGA	Thermogravimetric analysis
TPS	Thermoplastic starch
WF	Wood flour
WPC	Wood plastic composite

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