



Full length article

Environmental impact assessment of six starch plastics focusing on wastewater-derived starch and additives



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ARTICLE INFO

Keywords:

Starch plastic blends
Life cycle assessment
Reclaimed starch
Bio-based plastics
Additives
Compounding

ABSTRACT

Starch plastics are developed for their biobased origin and potential biodegradability. To assist the development of sustainable starch plastics, this paper quantifies the environmental impacts of starch plastics produced from either virgin starch or starch reclaimed from wastewater. A cradle-to-factory gate life cycle assessment is conducted for six different starch plastic compositions, which include representative amounts of additives such as compatibilisers. Starch plastics are shown to enable reductions in greenhouse gas (GHG) emissions and non-renewable energy use (NREU), but have higher eutrophication potential and require more agricultural land use compared to common petrochemical plastics. The GHG emissions savings are strongly influenced by the plastic's composition, with some grades offering an 85% reduction and others an 80% increase compared to the petrochemical counterpart (on a same weight-basis). Additives can account for up to 40% of the GHG emissions of starch plastics. The highest GHG savings are obtained when components such as PBAT and PBS are minimised, while starch, natural fibres and mineral fillers are maximised. Using reclaimed starch instead of virgin starch leads to modest decreases in NREU and GHG emissions (< 10% in most cases), but up to 60% reductions in eutrophication and agricultural land use.

1. Introduction

Starch plastics, blends of starch with other polymers, are being developed to contribute to environmental problems such as climate change and plastic pollution, due to their biobased origin and possible biodegradability. They are among the earliest commercialised biobased plastics (Shen et al., 2010) and are produced on industrial scale today. Starch plastic production capacity amounted to about 430 metric kilotonnes (kt)/yr in 2016, representing 10.3% of the global capacity of biobased plastics (Aeschelmann et al., 2017). At present, commercial starch plastics are developed mainly for film (e.g. biodegradable packaging, bags, agricultural mulching films), injection moulding (e.g. disposable tableware, flower pots), and foam applications (e.g. loose fill packaging). Flexible packaging accounts for about half of the starch plastic market, the remainder being used in agriculture, rigid packaging and consumer goods (Aeschelmann et al., 2017). Worldwide, the main crops used for dedicated ('virgin') native starch production are maize (82%), wheat (8%), potato (5%), and cassava (5%) (Le Corre et al., 2010). However, starch is also available in waste streams. For example, in the potato industry, starch-rich waste streams can amount to up to 15 kg for each 100 kg of potatoes processed (Janssens and Smit, 2016).

Native (i.e. unprocessed) starch cannot be used in plastics directly; its granular structure first needs to be disrupted using water, heat, and typically also plasticisers such as glycerol (Avérous, 2004). This yields *thermoplastic starch* (TPS), which can be processed like other plastics, e.g. in extrusion or injection moulding. However, pure TPS has poor mechanical properties and is susceptible to water, which limits its potential product applications. Therefore, TPS is often compounded (i.e. reactively extruded) with other polymers, typically aliphatic polyesters, to improve mechanical properties. Since hydrophobic polyesters and hydrophilic starch are immiscible, compatibiliser additives also need to be introduced to ensure good adhesion between the components, which improves technical performance (Yu et al., 2006). By varying the components used during compounding (native starch, co-polymers and additives), starch plastics with a wide range of technical properties can be obtained. Starch plastics can be biodegradable if TPS is blended with other biodegradable components.

The development of starch plastics has been driven by their potential environmental benefits, arising either from the use of biobased feedstocks or from desired biodegradability functionality. The environmental benefits and trade-offs of starch plastics compared to conventional petrochemical plastics can be quantified using life cycle

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Table 1

Composition and mechanical properties of starch plastic grades included in this study. Grades can be produced using either virgin or reclaimed starch.

Grade name		Starch/PLA	Starch/PBS	Starch/PHB	Starch/PBS/fibre	Starch/PLA/PBAT	Starch/re-PLA	PE	PP
Processing		Injection moulding			Extrusion				
Optimised for		General purpose	Thermal performance		Biodegradation	General purpose	Mechanical performance		
Composition ^a									
Starch (virgin/reclaimed)	Biobased	25%	16%	16%	19%	16%	15%		
PBAT	Petrochemical					18%	9%		
PLA	Biobased	43%				45%			
re-PLA	Biobased				14%		59%		
PBS	Petrochemical		55%		22%				
PHB	Biobased			55%					
Natural fibres	Biobased				28%				
Compatibiliser additive	Petrochemical	27%	7%	7%	8%	20%	10%		
Other additives	Various	5%	22%	22%	10%	< 1%	6%		
Properties ^b									
Young's modulus, GPa	ISO527	1.2	0.8–1.1	N.a.	N.a.	1.7–2.0	3.0	0.6–0.9	0.9–1.6
Tensile strength, MPa	ISO527	20–23	21	20	27	24	43	21–45	28–41
Density, g/cm ³	ISO1183	1.3	1.5	1.3	N.a.	1.3	1.3	0.9	0.9
Biogenic carbon content		67%	18%	85%	64%	56%	76%	0%	0%

^a Some totals do not add to 100% due to rounding. The category 'Other additives' includes mineral fillers, plasticisers, and processing aids. For reasons of competitiveness, it is not possible to disclose the compositions in greater detail than shown here. Abbreviations: PBAT = polybutyrate adipate-co-terephthalate; PLA = polylactic acid; re-PLA = post-industrial recycle PLA; PBS = polybutylene succinate; PHB = polyhydroxybutyrate.

^b Indicative testing results for starch plastics provided by Rodenburg (except biogenic carbon content). Biogenic carbon content is defined as the fraction of carbon derived from biomass in a starch plastic, and is derived from the composition information. Properties of PE and PP are taken from Ashby (2005) and may have been derived using different testing standards. Abbreviations: DNB = did not break; GPa = 10⁹ Pa; MPa = 10⁶ Pa; MJ = 10⁶ J.

assessment (LCA). Various LCAs have been conducted for blends of starch and polyesters with different compositions (see also the overview by Shen and Patel, 2008, who review methodology and results in depth). Patel (1999) focused on blends of starch with either 15%wt. polyvinylalcohol (PVOH) or 53–60%wt. polycaprolactone (PCL). Würdinger et al. (2002) studied a starch plastic consisting of 87%wt. starch and 13%wt. PVOH blends for loose fill applications. More recently, Guo and Murphy (2012) published an LCA for 5 product case studies for blends of starch (85–90%wt.) with 10%wt. PVOH and an undisclosed amount of minor additives. Beyond blends with PVOH, biodegradable bags made from 50%wt. starch blended with 50%wt. of either PCL, polybutylene succinate-co-adipate (PBSA) or polybutylene adipate-co-terephthalate (PBAT), and 30%wt. TPS blended with 70% wt. polyethylene (PE) have been studied in a streamlined LCA (James and Grant, 2005). Furthermore, a starch blend with polylactic acid (PLA) for thermoformed boxes was assessed by Suwanmanee et al. (2013) and Mahalle et al. (2014) studied the environmental impacts of a blend of 30%wt. wood fibres, 35%wt. PLA and 35%wt. TPS. Generally, these studies conclude that starch plastics can reduce energy use and greenhouse gas emissions when compared to petrochemical plastics on a same weight basis. When evaluating products instead of kg's, reduction potentials depend for instance on the specific application, source of starch, end-of-life scenarios and production route for polyesters (Guo and Murphy, 2012).

The LCA studies all focus on starch plastic production from virgin native starch. To our knowledge, the production of plastics from reclaimed starch has not been studied yet, although it is highly relevant e.g. in the context of the European Union's (EU) ambitions on efficient use of waste streams and cascading use of biomass (EC, 2012). Furthermore, previous LCAs have studied compositions consisting of two or three components. They do not include any additives or do not provide insights into their environmental significance, since they only focus on the main polymer resins. Additives² such as compatibilisers,

² IUPAC defines additive as 'Substance added to a polymer', and notes that the additive can be a polymer itself (Work et al., 2004).

plasticisers, processing aids and fillers are added in starch plastics to achieve a favourable balance between technical properties, processability, and cost. Although limited information is available on the environmental impacts of additives (van Oers et al., 2012), they can account for about of third of the weight of starch plastics and could thus strongly affect their environmental performance.

This paper addresses these shortcomings by presenting an attributional LCA for six commercial and exploratory starch plastics, focused on comparing virgin and wastewater-reclaimed starch and on quantifying the importance of additives. The grade compositions, consisting of four to six main components, are provided by a commercial starch compounder and thus include representative amounts of additives. The aim is to assist the research and development of starch plastic compounders by showing which components drive environmental performance. Specifically, the research 1) analyses the cradle-to-factory gate environmental impacts of six types of starch plastic granules, 2) evaluates the differences between using virgin and reclaimed starch in these six grades, and 3) quantifies the influence of additives, defined here as all components that are not starch or a polyester/natural fibre, on the environmental performance of starch plastics.

2. Methodology

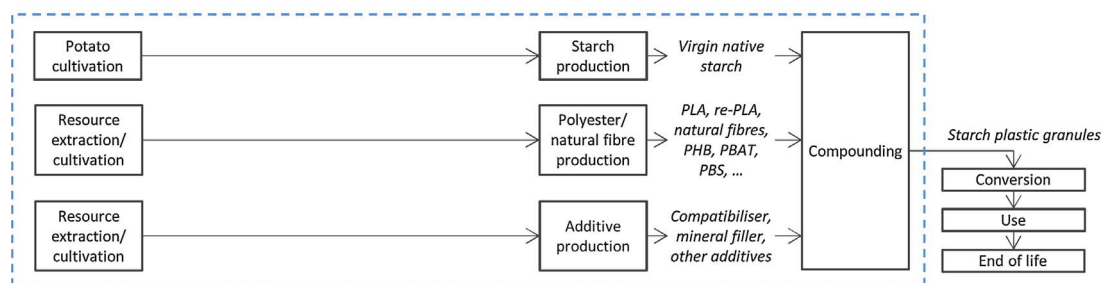
2.1. Goal and scope

2.1.1. Goal

This study follows the LCA methodology standardised in ISO 14040/14044 (ISO, 2006a,b). The primary goal is to quantify the environmental impacts of producing six types of starch plastics from cradle-to-factory gate. All starch plastic grades can be produced using either virgin starch or reclaimed starch, and both options are studied here (yielding 12 products in total).

The functional unit is 1 kg of starch plastic granules, at factory gate. Starch plastics are intermediate products that can be used for a range of different final products, and some of the grades are still being developed. Furthermore, the grades have different technical properties (see Table 1), but are most comparable to petrochemical low-density

Virgin starch product system



Reclaimed starch product system

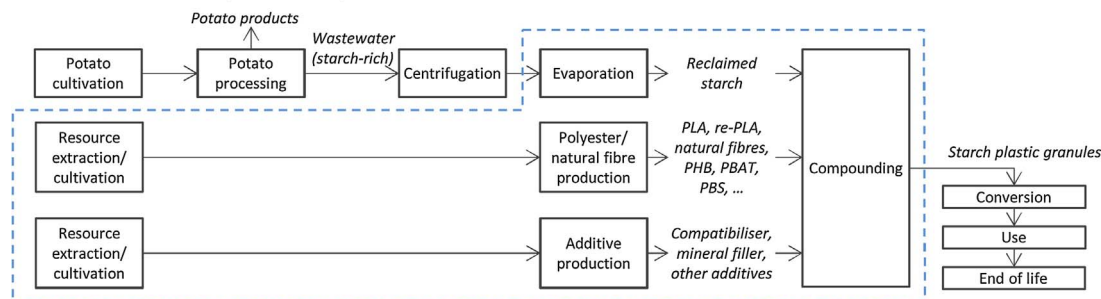


Fig. 1. Starch plastics production systems for virgin starch- and reclaimed starch-based production. Dotted line indicates the cradle-to-factory gate system boundaries of the analysis. Transport is not depicted.

polyethylene (LDPE) and polypropylene (PP). Based on the aim of this study (assisting R & D decisions for starch plastics compounders), we select a mass-based functional unit, rather than focusing on a specific product application. To put the results into context, they are compared to the environmental impacts of producing 1 kg of petrochemical LDPE and PP. Note that biodegradability, a defining characteristic and type of secondary functionality offered by starch plastics, is not included in the functional unit. The results of this study can be used to further quantify the cradle-to-grave environmental impacts for specific product applications.

An attributional LCA model is used, in line with situation C2 according to ILCD (EC-JRC, 2010). This accounting approach excluding interactions with other production systems is appropriate to support the development of products with relatively low production volumes. The study focuses on the typical, current production of starch plastics in the Netherlands. Thus, average Dutch data is used (or European if unavailable), and currently used technologies are studied (primary data was collected for 2014).

2.1.2. Scope and product systems

Fig. 1 shows the starch plastics production systems based on either virgin starch (top) or reclaimed starch (bottom). The cradle-to-factory gate scope includes the production of the different components, transport of all components to a central location, and compounding. The components include starch (virgin or reclaimed), petrochemical or biobased polyesters, and additives. After transportation to a central location, the starch and other components are compounded in an extruder. In the presence of water and plasticiser, the starch is destructured into thermoplastic starch due to the heat and shear forces generated by the extrusion screws, and blended with polyesters and additives to obtain the desired material properties. The compounding process includes cutting the extruded plastic into granules with a die cutter, as well as drying and cooling. The granules are then ready to be converted into final products (e.g. films, injection moulded products or foams). The subsequent conversion steps, use phase and end-of-life waste management are excluded in this study. The processes are described in detail in Section 2.2.

Table 1 provides an overview of the six specific starch plastic grades studied here, showing their names, composition, and technical properties. The grades are a selection of commercially available and experimental grades produced by Dutch starch plastic compounder Rodenburg Biopolymers BV. As mentioned above, either virgin or reclaimed starch can be used for all six starch plastics. Furthermore, note that additives are defined as all non-starch, non-polyester, and non-natural fibre components, accounting for 16–32%wt. of the grades studied.

Four of the grades are developed for injection moulding, and two for extrusion. Furthermore, two grades are general purpose grades for applications with limited technical requirements (Starch/PLA and Starch/PLA/PBAT), two are optimised for applications requiring higher heat deflection temperature (Starch/PBS and Starch/PHB), and one grade (Starch/re-PLA) was developed for so-called *geostructures* (e.g. underground reinforcement of slopes/dikes) and thus offers higher mechanical performance. The last grade (Starch/PBS/fibre) is a composite material optimised specifically for biodegradation (e.g. for temporary flower pots), although all grades are made from biodegradable components.

2.1.3. Environmental indicators

Four (midpoint and inventory-level) environmental indicators are included: GHG emissions (kg CO₂ eq.; 100yr timeframe) based on the IPCC's fourth assessment report (IPCC, 2007), eutrophication potential (g P eq.) based on CML Baseline (Guinée et al., 2002), agricultural land use (m²/yr), and non-renewable energy use (NREU; MJ). When using Ecoinvent data (see inventory details in Section 2.2), the last two indicators are respectively quantified using the ReCiPe Midpoint (H) (V1.05) and Cumulative Energy Demand (V1.08) methods in SimaPro (Goedkoop et al., 2009; PRé, 2016). The removal of biogenic CO₂ from the atmosphere during biomass cultivation is counted as a negative GHG emission (Section 2.2.3). Impact assessment methods were selected for consistency with literature sources (see modelling details in Section 2.2).

The selection of environmental indicators aims to capture both expected benefits and downsides of starch plastics to highlight potential

trade-offs (Broeren et al., 2017). On average, biobased products have lower GHG emissions but higher eutrophication impacts than conventional products (Weiss et al., 2012). Similarly, the use of renewable biomass as feedstock implies that biobased products may have lower NREU, with higher agricultural land use as a trade-off.

2.2. Life cycle inventory

2.2.1. Data sources

We first describe how the environmental impacts of producing all starch plastics components (Table 1) are determined, before discussing transport and compounding. For the former, a hierarchy of sources is applied. Where possible, datasets from peer-reviewed LCI databases are used, such as Ecoinvent v2.2 (Frischknecht et al., 2005). If these are not available or considered outdated (e.g. for PLA production), peer-reviewed academic literature sources are preferred. As the third alternative, modelling is used to determine the environmental impacts of some components. Generally, modelling assesses the required material/energy inputs for the most common production route based on literature, and uses the Ecoinvent database to determine the environmental impacts of those inputs. For chemical reactions (e.g. PBS production through polymerisation), material inputs are determined using reaction stoichiometry (e.g. for PBS, 50:50 molar ratio between butanediol and succinic acid), unless more detailed information is available. Table 2 provides details on data sources and modelling for each component. Note that important uncertainties in data and modelling assumptions are included in the sensitivity analysis discussed in Section 4.2.

Completing the product system shown in Fig. 1, after production all components are transported to a central location and compounded. Marine, rail, and road transport requirements are estimated based on the distance between component production sites and a central site in the Netherlands. The environmental impacts are based on Ecoinvent datasets. The compounding extruder runs on electricity. Its specific energy consumption (SEC) is based on Kent's (2013) empirically-derived equation for the average site SEC for extrusion processes, i.e. 0.53 kWh/kg of electricity use at a production rate of 100 kg/hr. In addition to the energy consumed by the extruder itself, site SECs (as opposed to machine SECs) include the energy used for auxiliary processes at extrusion sites (e.g. cooling, heating, lighting, offices, ...). Material losses during compounding are negligible.

To compare the findings to low-density polyethylene (LDPE) and

polypropylene (PP), the most recent PlasticsEurope data is used (PlasticsEurope, 2014a, 2014b). Petrochemical plastics require negligible agricultural land use. The comparison of starch plastics to petrochemical plastics is indicative only; they do not offer identical technical properties and are thus not functionally equivalent on a kg-basis.

2.2.2. Multifunctionality and allocation

In this attributional LCA, economic allocation is applied in cases of multi-output processes where subdivision or system expansion are not possible. Three (modelled) starch plastic components are notable for being derived from waste streams: reclaimed starch, re-PLA, and natural fibres. These are the most prominent cases of multifunctionality within the starch plastics production system. The waste flows from which these three components are derived are all undesired outputs of the processes that generate them and have either no or very limited economic value at present, and commodity markets do not exist (yet). Therefore, by default (see also re-PLA scenario in Section 4.1), a cut-off approach is used. The waste stream is thus considered free of environmental burdens, but subsequent processing to recover materials is assigned to those reclaimed materials. The production process and modelling of the three waste-derived components are now briefly reviewed; details for all other components are found in Table 2.

2.2.2.1. Reclaimed starch. Reclaimed starch is a by-product from the production of sliced potato products such as fries. Potato processing generates wastewater containing starch (around 2.5%wt.; Huang et al., 2003), which can be concentrated, e.g. with a decanter centrifuge, to a concentration of about 60% dry solids (Catarino et al., 2007). Doing so limits the chemical oxygen demand of the wastewater, and provides reclaimed starch as a saleable by-product. This activity (centrifugation) is not assigned to the reclaimed starch output due to missing information (discussed in Section 4.3.1). Before compounding, the starch is dried further to 18% moisture content by evaporation, using natural gas at an assumed 40% thermal efficiency.

2.2.2.2. Recyclate PLA. The manufacture of final PLA products can generate small scraps of PLA, e.g. from cutting smooth edges in thermoformed products. These scraps can be shredded, washed and dried, yielding post-industrial recyclate PLA (re-PLA). Re-PLA can be used in compounding of starch plastics without regranulation (pers. comm. Rodenburg, 2014). The cut-off approach means the PLA scraps

Table 2
Data sources used to determine the environmental impacts of producing the starch plastics components.

Components	Data type	Details
Reclaimed starch	Own modelling	Wastewater-reclaimed starch from potato products concentrated to 40% moisture content. Cut-off approach. The starch is subsequently dried to 18% moisture content using natural gas to evaporate water, assuming 40% thermal efficiency. This requires 2.36 MJ heat ^a /kg reclaimed starch.
Virgin starch	Database	Ecoinvent dataset for German potato starch ^a production at 20% moisture content. Modelled drying from 20% to 18% moisture content using evaporation for comparability with reclaimed starch (same method). This requires 0.16 MJ heat/kg virgin starch.
PBAT	Own modelling	Monomers assumed to be produced from 1,4-butanediol ^a , adipic acid ^a and terephthalic acid ^a (confidential ratios). Modelled based on Ecoinvent datasets. Corrected N ₂ O emissions of adipic acid production based on (Cok et al., 2014). Polymerisation energy assumed equal to that of PET polymerisation (PlasticsEurope, 2011), i.e. 3.8 MJ steam ^a /kg polymer and 3.3 MJ electricity ^a /kg polymer.
PLA	Literature	Data for 2014 NatureWorks PLA production (Vink and Davies, 2015).
re-PLA	Own modelling	Post-industrial NatureWorks PLA scraps from product manufacture. Cut-off approach. Modelled environmental impacts of shredding, washing and drying the scraps requiring 3.24 MJ heat ^a /kg re-PLA and 0.36 MJ electricity ^a /kg re-PLA (Jansen, 2012) using Ecoinvent data.
PBS	Own modelling	Petrochemical PBS. 1,4-butanediol ^a data from Ecoinvent. Modelled production of succinic acid based on Cok et al. (2014) and Ecoinvent datasets for maleic anhydride ^a and hydrogen ^a . Polymerisation energy assumed equal to PET polymerisation (PlasticsEurope, 2011), i.e. 3.8 MJ steam ^a /kg polymer and 3.3 MJ electricity ^a /kg polymer.
PHB	Literature	Impacts for PHB production from sucrose derived from cane sugar (Harding et al., 2007).
Compatibiliser	Database	Confidential compatibiliser additives. Environmental impacts determined based on datasets from PE International, Ecoinvent, and confidential literature.
Natural fibres	Own modelling	Plant stem fibres (plant type is confidential). Cut-off approach. Data on heat ^a and electricity ^a use for fibre extraction and drying provided by fibre supplier (confidential).
Other additives	Database	Ecoinvent datasets, updated economic allocation

^a Selected Ecoinvent datasets: Heat: Heat, natural gas, at industrial furnace > 100 kW/RER; Potato starch: Potato starch, at plant/DE; 1,4-butanediol: Butane-1,4-diol, at plant/RER; Adipic acid: Adipic acid, at plant/RER; Terephthalic acid: Purified terephthalic acid, at plant/RER; Steam: Steam, for chemical processes, at plant/RER; Electricity: Electricity, production mix RER/RER; Maleic anhydride: Maleic anhydride from the direct oxidation of *n*-butane, at plant/RER; Hydrogen: Hydrogen, liquid, at plant/RER.

are considered free of environmental burdens, but shredding impacts are allocated to the re-PLA.

2.2.2.3. (Waste) natural fibres. The natural fibres in this study are derived from plant stems normally treated as biological waste. At present, a small-scale process is used to extract the fibres from the stems. Data on the energy use of this process and subsequent drying was provided by the natural fibre supplier.

2.2.3. Biogenic carbon emissions

For all biobased components, biogenic carbon removed from the atmosphere during biomass cultivation is counted as a negative emission in this study, calculated based on the molecular formula of the component. This approach maintains carbon balances by keeping track of the physical carbon embedded in each material flow within the cradle-to-gate system boundaries. The approach is in line with e.g. the European Commission's Lead Market Initiative, which states that biobased carbon contained in products shall be deducted when calculating GHG emissions (EC, 2009), and with ISO 14067 on carbon footprints, which states that carbon storage in products should be calculated based on the amount of carbon contained in the product (ISO, 2013). It has also been applied in other LCAs of biobased materials (e.g. Cok et al., 2014; Kim and Dale, 2008; Tsiropoulos et al., 2015; Vink and Davies, 2015). Note that the carbon removal credit is also assigned to the waste-derived components as an exception to the cut-off approach discussed above (which implies cutting off all environmental impacts *and* credits associated with processes preceding the cut-off), meaning that e.g. virgin and reclaimed starch receive the same credits.³ If literature sources already accounted for carbon removal, we avoid double counting. Note that carbon removed from the atmosphere can be emitted again as CO₂ if it is fully oxidised during the product's end-of-life (outside the scope of this study). Furthermore, potential emissions related to (indirect) land use change are not included (see also Section 4.3.1).

3. Impact assessment results

Fig. 2 presents the environmental indicator results for the six starch plastics produced from either virgin starch or reclaimed starch, and shows the contribution of each component (for virgin starch). Unless noted otherwise, the discussion below focuses on virgin starch-based production.

The environmental impacts of starch plastic production vary greatly from grade to grade. For instance, the NREU (33–72 MJ/kg, when using virgin starch) and eutrophication (1.2–1.9 g P eq./kg) values differ by a factor 2.2 and 1.6 between the best- and worst-scoring grades, respectively. Gross GHG emissions (i.e. total emissions without crediting carbon removals) also differ by a factor 2 (1.8–3.7 kg CO₂ eq./kg). However, *net* GHG emissions (i.e. gross GHG emissions minus carbon removals) and agricultural land use vary more widely, with respectively a factor 8 and 4 between the lowest and highest grades. This is due to the low net GHG emissions of Starch/re-PLA (where carbon removals almost balance out the gross GHG emissions) and the low land use (0.3 m²/yr/kg) of Starch/PBS due to its limited use of biobased materials (18% biogenic carbon content; Table 1). No starch plastic grade scores best on all indicators, although Starch/re-PLA scores best or second-best on all indicators.

Using reclaimed starch (diamonds in Fig. 2) instead of virgin starch (squares) improves the environmental performance for all indicators and all grades. The improvements are minor for gross GHG emissions (not shown) and NREU (both 1.2–5.2%). Net GHG emissions decline by

3–24%. The improvements are more pronounced for eutrophication (19–41%) and agricultural land use (16–62%). These two indicators are (mainly) linked to the biomass cultivation stage, so the cut-off approach used for reclaimed starch results in larger differences. Conversely, NREU and GHG emissions of reclaimed starch are caused by the drying step, resulting in a smaller gap with virgin starch-based production (note that the carbon removal credit is constant).

Polyesters and additives are the largest contributors to all environmental indicators for starch plastics production. We discuss the breakdowns for virgin starch-based production (corresponding to the bars in Fig. 2), but they are similar for reclaimed starch. Polyesters account for 35–80% of NREU and gross GHG emissions. Similarly, additives (i.e. compatibilisers and other additives) can account for up to 46% for these indicators, which is the case for Starch/PLA where their mass contribution is also largest (Table 1). Conversely, for Starch/PBS, where smaller amounts of additives are used in combination with relatively energy-intensive polyesters, the additives only account for 9% of both indicators. For eutrophication and land use, polyesters and additives can dominate when they are biobased, e.g. accounting for 59% and 83% of Starch/PHB's eutrophication and land use, respectively. Furthermore, virgin starch itself is a minor contributor to NREU and gross GHG emissions (2–7%) but can account for up to 60% of agricultural land use or 40% of the eutrophication potential of starch plastics. As noted above, these impacts can be reduced substantially with reclaimed starch. Transport accounts for at most 5% of the studied indicators. Concluding, from the perspective of GHG emission reduction, components such as PBAT, PBS and compatibilisers should be minimised in starch plastics (as far as technical requirements allow), while reclaimed starch, re-PLA, natural fibres and mineral filler additives should be maximised.

Finally, Fig. 2 shows that starch plastics require less NREU and can reduce GHG emissions compared to petrochemical LDPE and PP on a kg-basis, whereas increased eutrophication and land use are trade-offs. NREU savings are 6–60%, and four of the starch plastics can reduce net GHG emissions by 3–81%. The two remaining grades, Starch/PBS and Starch/PLA/PBAT use energy-intensive components and/or have limited carbon removal, resulting in up to 80% higher net GHG emission than LDPE/PP. The eutrophication potential of starch plastics is 3–5 times higher when using virgin starch, and 2–4 times when using reclaimed starch. For the most part, this impact is linked to biomass cultivation, although electricity use (compounding) and some petrochemical polymers (e.g. PBS) also contribute.

The agricultural land use of starch plastics production is 0.3–1.3 m²/yr/kg when using virgin native starch, and 0.1–1.1 m²/yr/kg for reclaimed starch-based production. These figures can be put into context by considering NREU savings (compared to LDPE or PP) per area of agricultural land, i.e. in MJ/m²/yr. This expresses the 'land use efficiency' of starch plastics in reducing NREU, and can be used to compare different product systems that may be competing for agricultural land in a biobased economy (see e.g. Bos et al., 2012; Dornburg et al., 2003). For virgin starch-based production, Starch/re-PLA scores best on this metric, at up to 110 MJ/m²/yr when replacing LDPE. Conversely, Starch/PLA/PBAT replacing PP represents the worst case, as land use efficiency amounts to about 10 MJ/m²/yr. For reclaimed starch-based production, the lower land use (Fig. 2) yields higher NREU savings, ranging from 10 to 200 MJ/m²/yr. For comparison: depending on the biomass feedstock used, the NREU savings for bioethanol compared to petrol have been estimated to range from 14 (wheat starch) to 46 MJ/m²/yr (sugarcane)(Bos et al., 2012).

4. Discussion

This section interprets the results further by exploring alternative feedstocks scenarios (4.1), conducting a sensitivity analysis of the default results (4.2) and discussing other limitations of the work (4.3).

³ According to ISO 14044, if allocation cannot be avoided through system expansion or by subdividing the product system, all inputs (e.g. CO₂ removals) and outputs (process emissions) should be allocated uniformly. For reclaimed starch, one could argue that all carbon removals should be allocated to the main product (potato products) when conducting economic allocation. This interpretation is not followed here as it is out of line with similar studies on biobased materials and violates carbon balances.

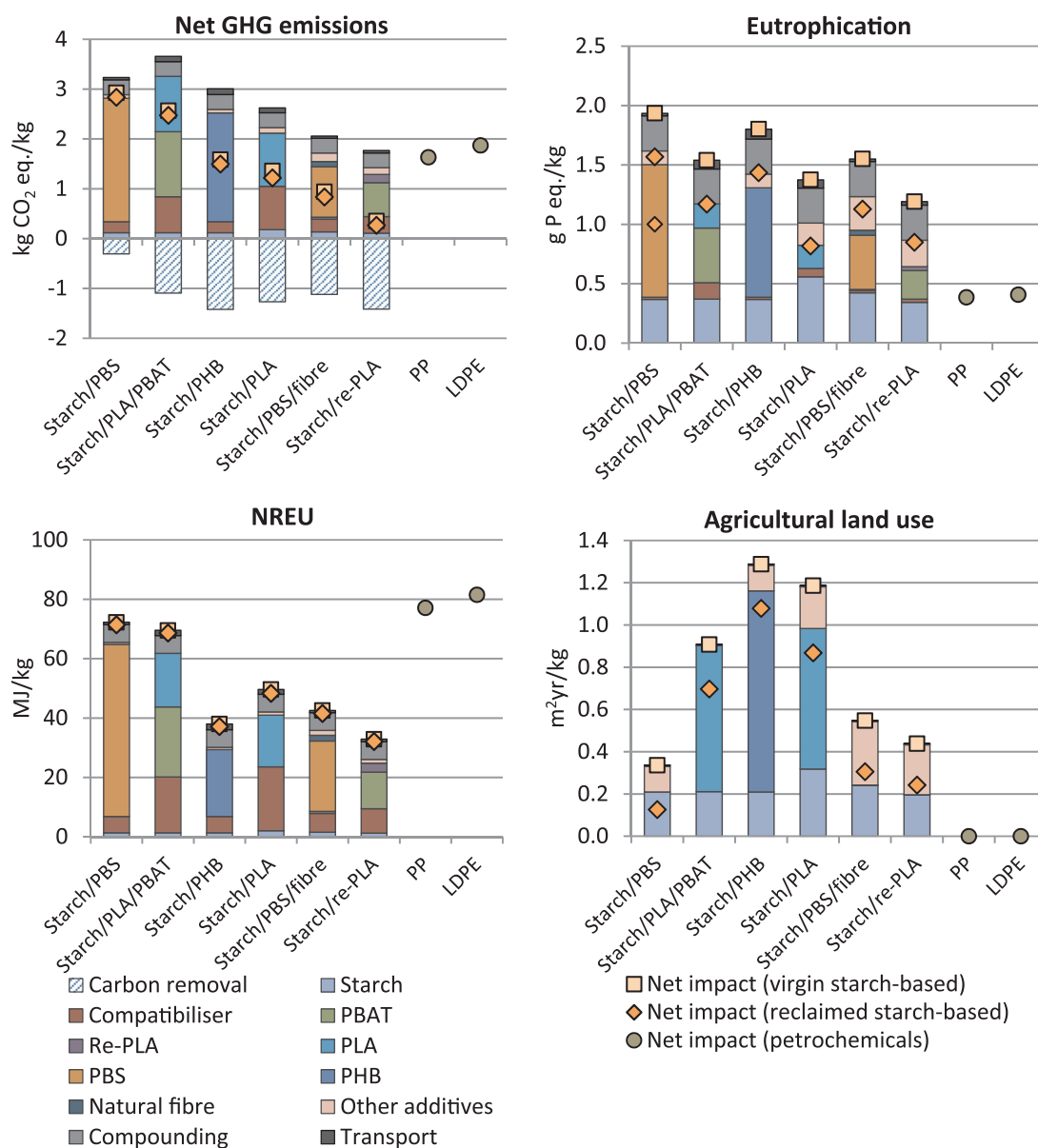


Fig. 2. Impact assessment results cradle-to-factory gate production of starch plastics and petrochemical references. Markers indicate the total (net) impact when using virgin starch (squares) or reclaimed starch (diamonds). The breakdown shown corresponds to virgin starch.

4.1. Alternative feedstock scenarios

The alternative feedstock scenarios investigate different production routes/assumptions for three starch plastics components, to provide insight into further improvement options (compared to the default analysis). The cases are introduced in Table 3. The results, shown in Fig. 3 below, are compared to the default results for virgin starch-based production.

Using partially biobased PBS (green triangles) or sugarcane-derived PLA (purple circles) leads to comparable trade-offs: lower NREU and (net) GHG emissions but higher eutrophication and agricultural land use. The savings in NREU and GHG emissions lie between 6 and 11% for the starch plastic grades concerned. The 10% reduction in Starch/PBS' GHG emissions is substantial, as it has the highest GHG emissions in the default analysis (Fig. 2). This suggests that the GHG emissions can be reduced further by increasing the use of biobased components. However, the increases seen for eutrophication and land use are large in both these scenarios, between 30% and 250% (the latter corresponding to the agricultural land use increase for Starch/PBS when using

partially biobased PBS). Increases in these two indicators can be expected for the biobased PBS scenario, as larger shares of the starch plastics are produced from biomass in this case, which in turn means more land requirements and (typically) more fertiliser use and eutrophication potential. The sugarcane PLA scenario represents only a change in feedstock but leads to similar results/trade-offs. Most notably, the eutrophication impact (per kg PLA) of sugarcane PLA is about four times higher compared to maize-based PLA. This finding is discussed further in Section 4.3.2.

For re-PLA, the waste valuation scenario (red diamonds) increases all environmental indicators compared to the default cut-off approach. For example, the GHG emissions per kg re-PLA increase almost fourfold, since it now also carries part of the burden of virgin PLA production. For starch plastics, this scenario leads to the largest changes for Starch/re-PLA, which uses more re-PLA than Starch/PBS/fibre (Table 1). Its net GHG emissions more than double, for instance. Although this scenario does not represent the current economic situation, it illustrates that the default results presented here are partly contingent on the availability of free waste streams to produce starch plastic components. If biological

Table 3
Overview of alternative feedstock scenarios.

Scenario	Rationale	Modelling changes	Grades affected
Partially biobased PBS	To produce PBS, the required succinic acid can be derived from carbohydrates instead of petrochemical sources (e.g. maleic acid or maleic anhydride from butane).	Switch to biobased succinic acid produced in Europe based on dextrose from maize (Cok et al., 2014). Average of direct crystallisation and electro dialysis routes.	Starch/PBS, Starch/PBS/fibre
Sugarcane-derived PLA	The PLA in the default analysis is derived from maize in the United States. Alternatively, sugarcane-derived lactic acid can be used for PLA production.	Switch to virgin PLA produced by Corbion in Thailand, based on Groot and Borén (2010).	Starch/PLA, Starch/PLA/PBAT
Re-PLA waste valuation	In a future biobased/circular economy, waste streams are valuable, which makes a cut-off approach for re-PLA less appropriate. Here, we assume that the scrap PLA from which re-PLA is made becomes a commodity.	Economic allocation to share the burdens of virgin PLA production (Vink and Davies, 2015) among PLA final product and scrap PLA. Price of scrap PLA assumed as 1/3 of virgin PLA.	Starch/re-PLA, Starch/PBS/fibre

waste streams become increasingly valuable in a biobased economy, the environmental impact of (partially) waste-derived starch plastics increase as well when economic allocation is used.

4.2. Sensitivity analysis

The sensitivity analysis quantifies the influence of important uncertainties in the LCA, one at a time. The cases and their underlying rationale are introduced in Table 4.

The results of the sensitivity analysis are shown in Table 5. For most grades and environmental indicators, the sensitivity cases fall within +/−10% of the default results. Net GHG emissions are the most volatile, especially for grades with a comparatively low default value such as Starch/re-PLA. Agricultural land use is not sensitive to the changing variables defined in Table 4. Overall, the results are not considered sensitive to the shredding energy consumption (either higher or lower) or to a substantial increase in the extrusion rate of compounding. For the latter, the SEC is inversely proportional to the production rate (since extruders have baseload energy use), meaning that low production rates lead to larger changes. The slow extrusion case (SEC: +66%) therefore leads to more substantial changes in all indicators except land use.

Furthermore, varying the composition of PBAT can lead to substantial changes (especially in net GHG emissions) for two starch plastic grades. As AA production has higher estimated GHG emissions than TA production, a high share of TA results in substantially lower net GHG emissions for starch plastics (−15 to −56%). As typical TA to AA ratios for PBAT used for starch plastics are not known, the default net GHG emission results for the Starch/PLA/PBAT and Starch/re-PLA grades are

somewhat uncertain and could be about 0.2 kg CO₂ eq./kg lower or higher.

Finally, assuming lower environmental impacts for PHB production based on literature strongly affects the results for Starch/PHB (containing 55% PHB). Its −146% change in net GHG emissions amounts to −0.7 kg CO₂ eq./kg starch plastic, making it the best-performing grade. At present no large-scale (e.g. >100kt/yr) PHB production facilities exist, and so the available environmental impact data is based on a variety of different production processes (e.g. fermentation technologies), resulting in substantially different impacts (Kim and Dale, 2005). Our default results are thus somewhat conservative (using higher environmental impact data). If PHB becomes a common component for starch plastics this uncertainty thus warrants further investigation.

4.3. Other uncertainties

4.3.1. Study scope

The purpose of this study is to support the development of more sustainable starch plastics. The focus on a broad variety of grades which are partly exploratory introduces limitations that should be kept in mind when interpreting the results. First, the cradle-to-factory gate scope means that differences in use phase functionality (e.g. resulting from mechanical property or density differences) are not considered. Furthermore, biodegradation is out of scope in this study, but should be considered in cradle-to-grave studies as a key feature of many starch plastic blends. In case of complete biodegradation, the carbon removed from the atmosphere (Fig. 2) would be converted into CO₂, CH₄, new biomass and/or residuals/metabolites (Wilde et al., 2013). However,

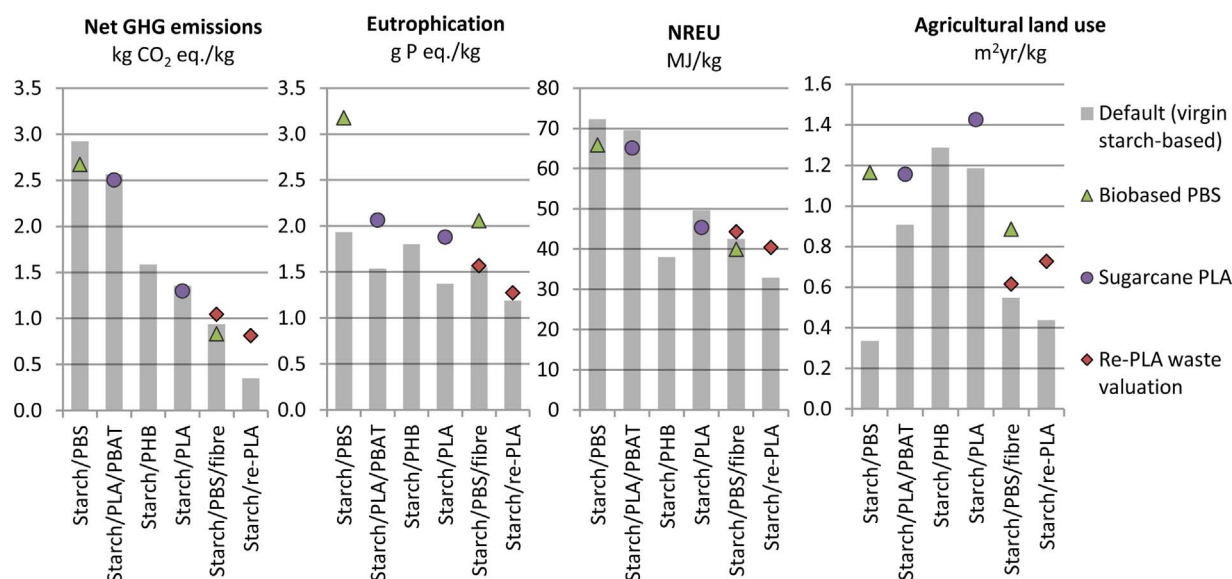


Fig. 3. Alternative feedstock scenarios – environmental indicators for cradle-to-factory gate starch plastics production (markers) compared to the default results (grey bars; Fig. 2).

Table 4
Sensitivity analysis cases.

Case	Details	Grades affected
PBAT composition	PBAT can be synthesised by combining 50%mol. 1,4-butanediol with different ratios of adipic acid (AA) and terephthalic acid (TA). Since the environmental impacts of producing the acid monomers are not equal, varying the AA:TA ratio influences the environmental performance of PBAT. A typical ratio used for starch plastics is not known due to confidentiality. Here we explore two extreme cases with either high AA, or high TA content.	Starch/PBAT, Starch/re-PLA
Re-PLA processing energy	This case investigates the influence of using the extremes of the confidence interval mentioned by Jansen, (2012), instead of the average (3.6 MJ/kg): - 5.4 MJ/kg - 1.8 MJ/kg	Starch/re-PLA, Starch/fibres
PHB environmental impacts	LCA studies on PHB derived from starch or sugar feedstocks come to strongly differing results. Here we assess the effect of switching from the default cradle-to-factory gate LCA results (NREU: 40 MJ/kg, net GHG emissions: 1.96 kg CO ₂ eq./kg) to more optimistic values from literature (Kim and Dale, 2008), i.e. NREU of –2.5 MJ/kg PHB, and net GHG emissions of –2.3 kg CO ₂ eq./kg PHB. Note that this analysis only studies GHG emissions and NREU due to lack of further information.	Starch/PHB
Extruder production rate	This study's default extruder production rate of 100 kg/hr results in an estimated site SEC of 1.9 MJ/kg granules (Kent, 2013). The effects of compounding starch plastics at a smaller and at a larger scale are investigated: - 10 kg/hr (3.15 MJ/kg) - 1000 kg/hr (1.38 MJ/kg)	All

the extent, products and rate of biodegradation are highly case-specific (depending e.g. on temperature, moisture, type of micro-organisms present), meaning that its GHG emissions strongly depend on the starch plastic's final product, use, and disposal. Depending on the product's use phase and end-of-life, the impact of delayed GHG emissions could also be considered (BSI, 2011). Second, it should be noted that the comparisons with LDPE and PP do not account for any additives used in these petrochemical plastics, which may be added to achieve strong technical performance.

Third, potential GHG emissions related to direct or indirect land use change (dLUC/iLUC) are not included in this study. In e.g. the PAS2050 LCA method, iLUC emissions are not taken into account, but dLUC emissions should be quantified if the agricultural land has been converted in the past 20 years (BSI, 2011). This 20 year timeframe means dLUC emissions are expected to be minor for the main biomass feedstocks considered in this study: European (virgin) potato starch and US corn (for PLA). For the latter, dLUC is estimated to add about +2% to the on farm emissions (Blonk Agri-footprint, 2015). For sugarcane-derived materials, dLUC can be more significant, e.g. for Brazilian sugarcane, dLUC is estimated to account for about 75% of on farm emissions (Blonk Agri-footprint, 2015). In this study, only the environmental impacts of PHB are derived from a sugarcane-based production route (Harding et al., 2007). However, this source is an exploratory LCA study that does not study an existing industrial production route. The sugar source is therefore not defined, and the influence of potential dLUC emissions cannot be estimated. Concluding, including dLUC emissions would not strongly have influenced our default results. Nonetheless, potential dLUC emissions should be taken into consideration during material sourcing decisions.

More generally, expanding biobased economies can avoid the conversion of pristine lands and thus the risk of LUC emissions by taking a holistic approach towards land and the services it provides, for instance focusing on closing yield gaps, utilisation of degraded/marginal lands and good agricultural management (Brinkman et al., 2017). Furthermore, it should be noted that reclaimed starch and other reclaimed materials are not directly responsible for land use, and can therefore be used without any risk of dLUC or iLUC.

Lastly, the results for reclaimed starch-based plastics do not include the environmental impacts of using a decanter centrifuge to concentrate the starch to 40% moisture content (before evaporation). According to e.g. the ILCD Handbook (EC-JRC, 2010), the reclaimed starch is only partly responsible for these impacts, as removing starch from the (negative value) wastewater is considered a form of waste treatment for the main potato product (e.g. fries). Furthermore, the energy

consumption of centrifugation is likely far lower (e.g. 1–10 kWh/m³ feed) than the subsequent evaporation (10–1000 kWh/m³ feed; Olivieri, 2014). Assuming a high value of 10 kWh/m³ and a 50% allocation factor for reclaimed starch, increases the gross GHG emissions of all starch plastic grades (based on reclaimed starch) by less than 1%. Omitting centrifugation has therefore not strongly influenced the results.

4.3.2. Uncertainty in environmental indicators

Combining environmental impact data from a variety of sources can be problematic if different impact assessment models were used to derive them. This is primarily an issue for eutrophication, as the other indicators either have broadly accepted impact assessment methods (e.g. GHG emissions based on IPCC models) and/or are ('uncharacterised') inventory-level indicators. All eutrophication potential values used in this study are derived using the CML LCIA method (when the method is stated, which is the case for nearly all components). Nonetheless, some remarkable results were obtained. For example, Section 4.1 showed that sugarcane-based PLA was estimated to have four times higher eutrophication potential than maize-based PLA, based on two LCA studies from PLA producers. In the case of PLA, given the limited information available it is not possible to discern whether the factor four difference is 'real', i.e. due to actual differences in eutrophication-related emissions for instance due to fertiliser application differences, or a methodological artefact, e.g. due to different assumptions in modelling run-off of N- and P-compounds. Such discrepancies in eutrophication potential estimates are not limited to materials produced from different feedstocks, but even occur for the exact same production routes. For example, the most recent updates of the eco-profiles for LDPE and PP (used in this study) show an increase in eutrophication potential of up to 150% compared to their 2008 predecessors, in which specific substances were not included (PlasticsEurope, 2014a, 2014b).

These two cases illustrate that eutrophication results can be troublesome to interpret and that eutrophication-relevant emissions can be difficult to model. We thus consider our eutrophication results subject to higher uncertainties than the other environmental indicators. Considering that eutrophication is a relevant issue for biobased products (Broeren et al., 2017; Weiss et al., 2012), this situation can be improved by adopting consistent inventory modelling practices in LCAs and by providing more methodological transparency in studies by material producers.

Table 5 Sensitivity analysis results (see variables defined in Table 4). Percentages express differences compared to the (virgin starch-based) default results shown in Fig. 2.

	Net GHG emissions										Eutrophication									
	Starch/PBS	Starch/PLA/PBAT	Starch/PHB	Starch/PLA	Starch/PBS/fibre	Starch/re-PLA	Starch/PBS	Starch/PLA/PBAT	Starch/PHB	Starch/PLA	Starch/PBS/fibre	Starch/re-PLA	Starch/PBS	Starch/PLA/PBAT	Starch/PHB	Starch/PLA	Starch/PBS/fibre	Starch/re-PLA		
PBAT: high TA content	-15%					-56%					-7%							-5%		
PBAT: high AA content	11%					41%					5%							4%		
Re-PLA shredding energy: low						-24%												-1%		
Re-PLA shredding energy: high						24%												1%		
PHB: low impacts			-146%										0%							
Extrusion: slow	7%	8%	12%	14%	21%	55%	10%	11%	14%	10%	13%	14%	11%	11%	14%	12%	16%	16%		
Extrusion: fast	-1%	-1%	-1%	-1%	-2%	-6%	-1%	-1%	-1%	-1%	-1%	-1%	-1%	-1%	-1%	-1%	-1%	-2%		
	NREU										Agricultural land use									
	Starch/PBS	Starch/PLA/PBAT	Starch/PHB	Starch/PLA	Starch/PBS/fibre	Starch/re-PLA	Starch/PBS	Starch/PLA/PBAT	Starch/PHB	Starch/PLA	Starch/PBS/fibre	Starch/re-PLA	Starch/PBS	Starch/PLA/PBAT	Starch/PHB	Starch/PLA	Starch/PBS/fibre	Starch/re-PLA		
PBAT: high TA content	-5%					-6%														
PBAT: high AA content	4%					4%														
Re-PLA shredding energy: low						-1%												0%		
Re-PLA shredding energy: high						1%												0%		
PHB: low impacts			-56%											0%						
Extrusion: slow	5%	6%	10%	8%	9%	12%	1%	10%	8%	10%	5%	1%	0%	0%	0%	1%	1%	1%		
Extrusion: fast	-1%	-1%	-1%	-1%	-1%	-1%	0%	-1%	-1%	-1%	-1%	0%	0%	0%	0%	0%	0%	0%		

5. Conclusions

This cradle-to-factory gate LCA of six starch/polyester plastic blends aims to support the future development of starch plastic grades, and distinguishes itself from previous work by studying a broad range of compositions, by comparing virgin- and reclaimed starch-based plastics and by including the additives required to optimise their technical performance. Compared to common petrochemical plastics on a same weight-basis, starch plastics can reduce net GHG emissions (up to 80%) and NREU (up to 60%), but can have higher eutrophication potential (up to 400%) and require agricultural land (0.3–1.3 m²yr/kg). Per m²yr, starch plastics are estimated to save between 10 and 200 MJ when replacing LDPE or PP on a kg basis. Additives can account for up to 40% of a starch plastic’s net GHG emissions.

Several recommendations for starch plastic compositions can be derived from the analysis. As major contributors to the bulk of the environmental impacts of starch plastics, components such as PBAT, PBS and the compatibiliser additive should be minimised (within technical performance limits). Conversely, higher shares of (reclaimed) starch, re-PLA, natural fibres and mineral fillers minimise a starch plastic’s GHG emissions. Further reduction options can come from increasing the use of more biobased components such as partially biobased PBS.

Using reclaimed starch instead of virgin starch improves all environmental indicators for starch plastics. The savings are relatively small (mostly < 10%) for GHG emissions and NREU, but substantial for eutrophication (up to 40% improvement) and agricultural land use (up to 60%), indicators linked to the biomass feedstock cultivation phase. Using reclaimed starch also reduces the risk of iLUC emissions. Considering the EU’s bioeconomy strategy, the use of potato processing wastewater for starch plastic production can be compared with other potential uses to identify the most resource-efficient solutions.

Acknowledgments

The authors are grateful to Jeroen van Soest and Thijs Rodenburg (Rodenburg Biopolymers BV) for enabling and supporting this study. The research was partly funded by the Dutch Ministry of Economic Affairs (grant number: BO-21.02-001-180) under the Biobased Performance Materials research programme (subproject Feasible).

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