Resources, Conservation & Recycling 127 (2017) 246–255

Contents lists available at ScienceDirect

Resources, Conservation & Recycling

journal homepage: www.elsevier.com/locate/resconrec

Full length article

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

Martijn L.M. Broeren*, Lody Kuling[1], Ernst Worrell, Li Shen

Copernicus Institute of Sustainable Development, Group Energy and Resources, Utrecht University, Heidelberglaan 2, 3584CS, Utrecht, The Netherlands

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

* Corresponding author.
E-mail addresses: m.l.m.broeren@uu.nl (M.L.M. Broeren), lody@blonkconsultants.nl (L. Kuling), e.worrell@uu.nl (E. Worrell), l.shen@uu.nl (L. Shen).
[1] Present address: Blonk Consultants, Gravin Beatrixstraat 34, 2805PJ Gouda, The Netherlands.

http://dx.doi.org/10.1016/j.resconrec.2017.09.001
Received 6 July 2017; Received in revised form 29 August 2017; Accepted 3 September 2017
Available online 22 September 2017

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 recyclate 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 = 10^9 Pa; MPa = 10^6 Pa; MJ = 10^6 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. Additives[2] such as compatibilisers, 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

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