Institution: University of Bath		
Unit of Assessment: A8 Chemistry		
Title of case study: Development of Polylactic Acid (PLA) as a market-leading bio-based plastic		
Period when the underpinning research was undertaken: 2006 – 2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Prof Matthew Davidson	Whorrod Professor of Sustainable Chemical Technologies	September 1999 - present
Prof Chris Chuck	Professor, previously Reader, Lecturer, KTA Fellow, Research Officer	December 2007 – August 2008; September 2008 – March 2009; September 2010 - present
Period when the claimed impact occurred: 2014 - 2020		
Is this case study continued from a case study submitted in 2014? No		

1. Summary of the impact

With growing environmental concerns around the use of plastics there has been an increasing focus on the use of bio-based polymers. University of Bath research has developed catalytic approaches to support the production of green and sustainable polymeric materials. These have enabled the production of the bio-based thermopastic polymer polylactic acid (PLA) for use in commodity plastic products, through collaboration with industrial partner Total Corbion PLA (joint patents filed in 2014) underpinning industrial scale production (begun 2018) and commercialised sales. The impact includes construction of a 75,000 tonne capacity PLA manufacturing plant (2018), a USD100,000,000 investment that increased worldwide production of PLA by 50%, a volume representing market value of approximately USD150,000,000 per annum. The company has now announced its intention to build the first world-scale PLA plant in Europe.

2. Underpinning research

There is growing interest in bio-based and degradable plastics as a result of the negative impacts that traditional petroleum based plastics have on climate and health. Polylactic acid (PLA) is a bio-based biodegradable thermoplastic produced from renewable resources such as starch or sugar from corn or sugar cane, that offers an attractive plastic alternative. Development of catalysts for the manufacture of these bio-based plastics at scale is vital for a cost-effective and sustainable industrial process. However, very few sustainable initiators/catalysts are able to operate selectively to give high-value polymer in solvent-free conditions and at the high temperatures required for industrial production.

A 20 year programme of research within the Centre for Sustainable and Circular Technologies (CSCT) at University of Bath, led by Professor Davidson, has sought to develop such environmentally friendly homogeneous catalysts. Previous collaborative research with Johnson Matthey focused on the replacement of heavy metal catalysts in the manufacture of poly(ethylene terephthalate) (PET) and poly(urethane) (PU) [REF2014 Case Study]. Related benign Ti and Zr complexes were also found to be active catalysts for the ring-opening polymerisation (ROP) of cyclic esters such as ε-caprolactone and lactide with excellent levels of conversion and control [1,2,3].

To develop this concept towards PLA, new catalysts (with the embedded green benefit of avoiding heavy metals) had to be developed and optimised. Collaborative research between University of Bath and Total Corbion PLA (and predecessors Corbion and PURAC Biochem BV) has pursued this since 2010, addressing the need to identify catalysts that are highly selective in solvent-free environments and at high temperatures to enable industrial scale production of PLA; that replace traditional heavy metal-based catalysts; and that produce PLAs with defined and controlled physical and mechanical properties to broaden the scope of their application.

Initially this collaborative research showed that stereoselective ring-opening polymerisation (ROP) of racemic lactide (*rac*-LA) under solvent-free conditions and supported by amine tris(phenolate) ligands offered an unprecedented combination of high stereocontrol ($P_r > 0.90$) and high activity (95% conversion in less than 30 minutes). This demonstrated for the first time that living and highly stereoselective ROP of *rac*-LA can be achieved in the bulk with high conversion on a timescale and at a temperature that are compatible with continuous processing technologies [4].

Subsequent research increased the activity and stability of the ROP catalysts, in contrast to commercially available group 4 metal alkoxides, this new group 4 catalyst was highly active in facilitating a more than 99% polymerisation to PLA within three hours, offering the potential of group 4 complexes as initiators for the commercial production of PLA [4].

This led to the development of a catalytic process for PLA production that was patented, based on Bath research and held by Total Corbion PLA (formerly Corbion, PURAC) [5, 6]. Using a new Group 4 metal PLA catalyst, mixing lactide and a metal-coordination compound (at least one of Zr and Hf) as polymerisation catalyst provided a benign tin-replacement catalysis process for PLA production at industrial scale [5, 6] and underpinned development of Total Corbion's PLA production capability. This collaborative research continues; Dr Gerrit Gobius du Sart (Total Corbion PLA Chief Polymer Scientist) is a Visiting Industrial Fellow in CSCT.

3. References to the research

[1] Chmura, AJ, **Davidson, MG**, Jones, MD, Lunn, MD & Mahon, MF, 2006, 'Group 4 complexes of amine bis(phenolate)s and their application for the ring opening polymerisation of cyclic esters', *Dalton Transactions*, vol. 2006, no. 7, pp. 887-889. https://doi.org/10.1039/b513345a (with industrial co-authors, Johnson Matthey)

[2] Chmura, AJ, **Davidson, MG**, Jones, MD, Lunn, MD, Mahon, MF, Johnson, AF, Khunkamchoo, P, Roberts, SL & Wong, SSF, 2006, 'Group 4 complexes with aminebisphenolate ligands and their application for the ring opening polymerization of cyclic esters', *Macromolecules*, vol. 39, no. 21, pp. 7250-7257. https://doi.org/10.1021/ma061028j

[3] Chmura, AJ, **Davidson, MG**, Frankis, CJ, Jones, MD & Lunn, MD, 2008, 'Highly active and stereoselective zirconium and hafnium alkoxide initiators for solvent-free ring-opening polymerization of *rac*-lactide', *Chemical Communications*, vol. 2008, no. 11, pp. 1293-1295. https://doi.org/10.1039/b718678a

[4] **Chuck, CJ**, **Davidson, MG**, **Gobius Du Sart, G**, Ivanova-Mitseva, PK, Kociok-Kohn, G & Manton, LB, 2013, 'Synthesis and structural characterization of group 4 metal alkoxide complexes of *N, N, N ',N '*-tetrakis(2-hydroxyethyl)ethylenediamine and their use as initiators in the ring-opening polymerization (ROP) of *rac* -lactide under industrially relevant conditions', *Inorganic Chemistry*, vol. 52, no. 19, pp. 10804-10811. https://doi.org/10.1021/ic400667z Co-authored with Industrial Partner Corbion

[5] Patent (EPO): Method to manufacture PLA using a new polymerization catalyst, Filed May 2013, EP13166273A, Published as EP2799462A1, November 2014. Inventors Gerrit Gobius du Sart (PURAC Biochem BV), **Matthew Davidson** (University of Bath) and **Christopher Chuck** (University of Bath), Assignee is PURAC Biochem BV.

https://worldwide.espacenet.com/patent/search/family/048193185/publication/EP2799462A1?q=pn%3DEP2799462A1%3F

[6] Patent (US): Method to manufacture PLA using a new polymerization catalyst, Filed April 2014, Published March 2016 US-20160075821-A1, Granted May 2018 US-9957350-B2. Inventors Gerrit Gobius du Sart (PURAC Biochem BV), **Matthew Davidson** (University of Bath), **Christopher Chuck** (University of Bath). Assignee is PURAC Biochem BV.
https://patentimages.storage.googleapis.com/18/e7/db/c9c591b1e5a1ca/US9957350.pdf

Direct industrial / translation funding
Total of GBP954,000 including: Royal Society Industry Fellowship (**M G Davidson**) 1999-2003 (GBP250,000); Industrial PDRA (ICI Synetix, now Johnson Matthey) 2002-2004 (GBP134,000); EPSRC/TSB Link Project (with ICI Synetix, now Johnson Matthey) 2004-2007 (GBP200,000); Knowledge Transfer Account Award and Industrial co-funding (with Purac, now Corbion Purac) 2010-2013 (GBP270,000)

4. Details of the impact

Polylactic acid (PLA) is a bio-based and biodegradable polymer that offers a more environmentally friendly alternative to traditional plastics with its reduced carbon footprint and manufacture from renewable resources. PLA is used in multiple industries including food packaging, oil and gas and automotive. Worldwide PLA had a estimated market worth of USD1,200,000,000 in 2018, with a calculated annual growth rate (CAGR) of 19.8% [A].

University of Bath research has directly informed the manufacturing processes of PLA and commercialisation activities of a multinational company, Total Corbion PLA. Specifically, the Bath research and generated IP [5, 6] led to:

- Development of a catalytic process for the manufacture of PLA at industrial scale [5, 6] leading to establishment of an initial demonstrator plant and, in 2017, a 1,000 tonnes per annum pilot plant [B];
- USD100,000,000 Investment into a new manufacturing plant, enhancing production capacity of PLA to 75,000 tonnes per annum (a growth world-wide of 50%) and operational in late 2018 [B];
- Recent new investment in a manufacturing plant in Europe;
- Reducing the environmental impacts of plastic.

This impact has been achieved using the Bath research insights into catalysts, collaborative research with industry partners, then through IP protection and full commercialisation [text removed for publication] [C].

Total Corbion PLA is a multinational based in the Netherlands, established in 2016 [D] by a joint venture between Total and Corbion PURAC, and evolved from PURAC Biochem BV. They have become a global leader in the marketing, sales and production of polylactide [E, F].

Implementing the catalytic process for the manufacture of PLA at industrial scale

In 2013, the developed method for manufacturing PLA [5] was implemented in small scale technology. This successful Corbion demonstrator, together with the evident high growth of the market for PLA, led to the construction of a 1000 tonnes per annum pilot and product development plant (announced 2014, operational December 2017), a 75,000 tonnes per annum manufacturing scale plant (operational 2018) and the announcement in 2020 of a new 100,000 tonnes per annum plant in France (scheduled to be operational in 2024).

USD100,000,000 Investment into a new manufacturing plant to enhance production capacity

The manufacturing scale plant was funded through a Joint Venture company (established November 2016), more than USD100,000,000 investment offering a completely new business opportunity for Total Corbion PLA [E, F]. This plant came online (in 2018, in Rayong, Thailand); its 75,000 tonnes per annum capacity represents an approximately 50% increase of world capacity for production of the important sustainable polymer PLA [G], with a projected market value of approximately USD150,000,000 per annum. The plant produces a wide range of Luminy® PLA resins, products that serve the needs of a global customer base, in 2019 over 350 customers worldwide and in a wide range of markets, including packaging, 3D printing and automotive sectors [H]. In addition, and adding commercial value for the established plant, it is co-located with integrated 100,000 tonnes per annum lactide manufacturing capability, and with the 1000 tonnes per annum pilot plant used for new product development [B]. This adds to the Total Corbion PLA materials portfolio, based on a fully integrated production chain from green feedstock to PLA [G].

In 2020, Corbion and Total announced their intention to build a further 100,000 tonnes per annum capacity PLA manufacturing plant through the Total Corbion PLA joint venture. This will add to the Thailand plant and will be the first world-scale PLA production facility in Europe [H]. This will make the company the world's number 1 producer of PLA.

Reducing the environmental impacts of plastic

Total Corbion PLA have carried out life cycle assessment of the environmental effect of plastics and the consequent benefits of PLA adoption [G, I]. This analysis shows that from the cradle-to-gate perspective, considering the uptake of carbon dioxide in the PLA molecule, the global warming potential (GWP) is only 501kg CO_2 equivalent per tonne PLA [I, J]. The Luminy® PLA produced by Total Corbion PLA are thus estimated to provide a 75% reduction in carbon footprint compared to most traditional fossil-based plastics; this arises from both the green feedstocks used in the manufacturing process and the biodegradeable nature of PLA polymer.

"*From a cradle-to-gate perspective the Global Warming Potential (GWP) of PLA is confirmed to be only 500g CO_2 per kg of PLA*" says the Senior Marketing Director at Total Corbion PLA, "*which is roughly a 75% reduction in carbon footprint versus most traditional plastics*" [J].

5. Sources to corroborate the impact

[A] Grand View Research Inc., Market Research report, October 2020. https://www.grandviewresearch.com/industry-analysis/polylactic-acid-pla-market

[B] Corbion Annual Report 2018. https://annualreport.corbion.com/FbContent.ashx/pub_1000/downloads/v200312101738/Corbion_AR2018.pdf (pp.21, 69-70)

[C] [text removed for publication]

[D] Corbion Press Release 2016: Total and Corbion form a Joint Venture in bioplastics 2016 http://www.corbion.com/media/press-releases?newsId=1026123

[E] Article, Business Focus magazine, March 2020. https://www.businessfocusmagazine.com/2020/03/31/total-corbion-pla-a-new-kind-of-plastic/

[F] Total Corbion Website. https://www.total-corbion.com

[G] Corbion Annual Report 2019. https://annualreport.corbion.com/FbContent.ashx/pub_1000/downloads/v200415100131/Corbion_annual_report_2019.pdf (p. 23)

[H] Article, Agro & Chemistry magazine, Netherlands, September 2020. https://www.agro-chemistry.com/news/corbion-and-total-to-build-first-world-scale-pla-plant-in-europe/

[I] Morão, A. & de Bie, F. (2019) Life Cycle Impact Assessment of PLA Produced from Sugarcane in Thailand. Journal of Polymers and the Environment volume 27, (pp2523–2539) https://link.springer.com/article/10.1007/s10924-019-01525-9

[J] Article, Packaging Europe magazine, October 2019. https://packagingeurope.com/low-carbon-footprint-of-pla-confirmed-by-peer-reviewed-life-/