Cambridge
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POLYHYDROXYALKANOATES:
PLASTIC THE WAY NATURE INTENDED?

INDUSTRIAL AND ENERGY

EXECUTIVE SUMMARY

Plastic accumulation in the natural environment is one of the most visible forms of environmental pollution caused by business. As a result of continual exposure to images of oceans full of plastic, consumers are becoming increasingly concerned about single-use disposable plastic items and plastic packaging.

For brands and manufacturers, the search is on for alternatives to conventional plastics – solutions that bring all of the cost, marketing and convenience benefits of plastic, without the environmental baggage.

Polyhyroxyalkanoates (PHAs) are a class of bio-derived, biodegradable polymers which could fit the bill. PHAs provide a tunable property set which provides unparalleled potential for a bioplastic to substitute fossil fuel derived plastics in a wide range of applications. In particular, the superior high temperature performance of PHAs significantly extends the addressable number of applications for bioplastics, beyond those which can be served by the most common bioplastic PLA.

With costs now approaching parity with conventional polymers, overcoming manufacturing challenges is the last major hurdle preventing wide scale adoption of PHAs.

PHAS ARE BIO-BASED, BIODEGRADABLE PLASTICS, PRODUCED BY FERMENTATION FROM A RANGE OF FEEDSTOCKS, INCLUDING WASTE.

The term bioplastics is an umbrella term which describes:

- conventional polymers derived all or in part using drop-in, bio-based feedstocks,
- polymers which are fossil fuel derived but are biodegradable
- polymers which are both bio-derived and biodegradable.

Polyhydroxyalkanoates or PHAs are an emerging class of bioplastics in the latter category, i.e. they are bio-based and biodegradeable. PHAs are produced by bacterial fermentation using bio-derived feedstocks – including waste – and thus are an alternative to fossil fuel-derived plastics.

Bioplastics are bio-based, biodegradable or both (European Bioplastics)

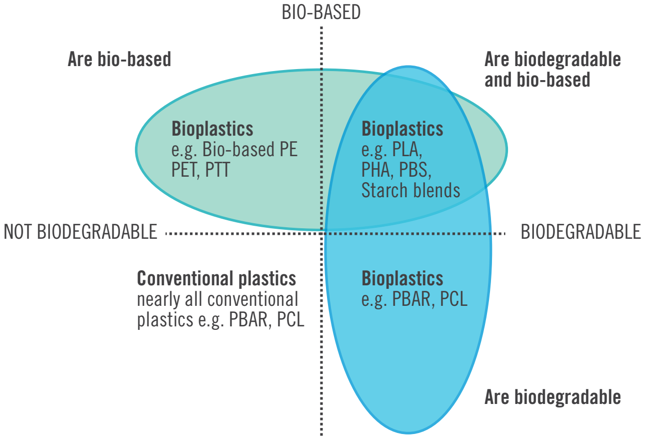

Figure 1: Types of bioplastics. Reproduced with permission from European Bioplastics https://www.european-bioplastics.org/

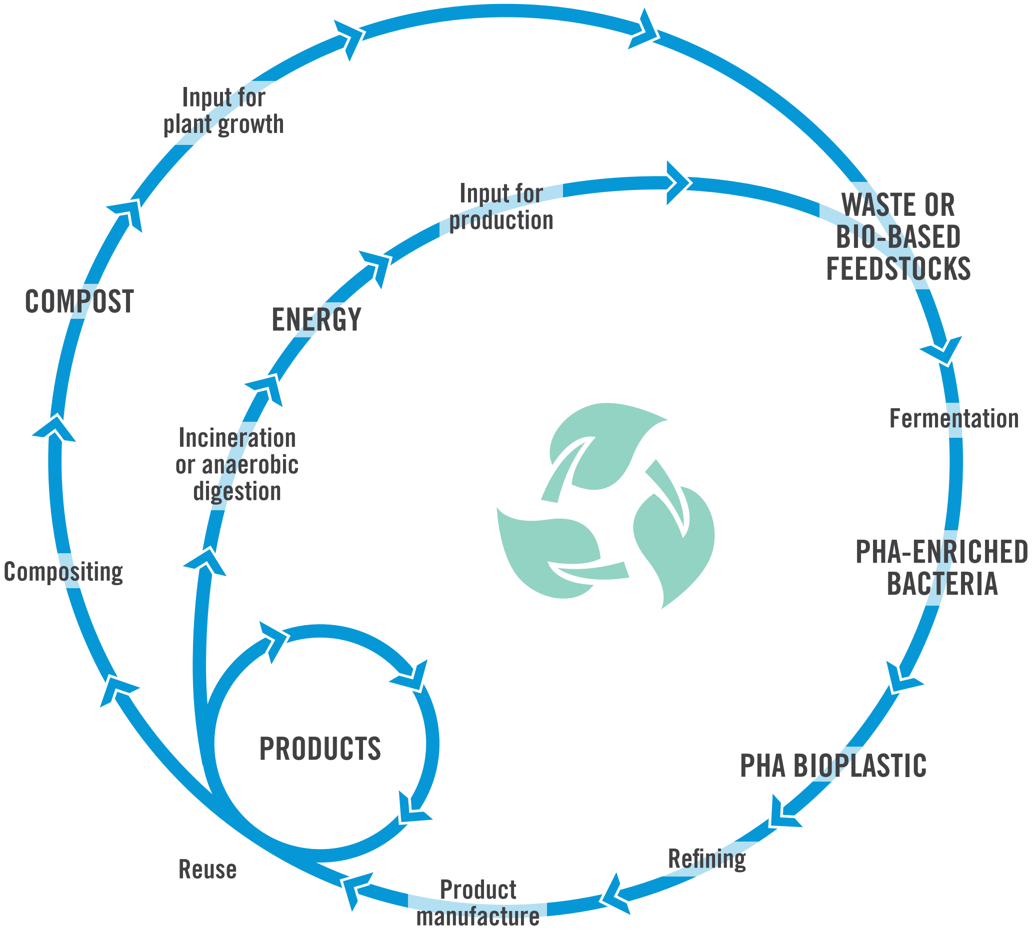

Figure 2: PHA lifecycle

THERE ARE MANY DIFFERENT PHAS WITH A VERY WIDE RANGE OF PROPERTIES, EXPANDING THE RANGE OF APPLICATIONS BEYOND THOSE THAT CAN BE SERVED BY MORE COMMON BIOPLASTICS.

The chemical composition of PHAs can be tuned depending on the monomer subunits used and in which combinations. PHAs are produced either as homopolymers or copolymers. Homopolymers consist of one type of PHA throughout the entire structure – such as pure P3HB or P4HB (see Figure 1). Copolymers on the other hand are made up of two or more different PHAs, randomly distributed throughout the structure of the polymer chain. Most common industrially produced PHAs are limited to using P3HB and one other PHA as the co-monomer (the other monomer present in the copolymer).

These various PHAs have a wide range of properties which can be tailored to different applications. In general, PHAs are biodegradable, compostable thermoplastics.

Because the PHA family contains a wide variety of different polymers which can be co-polymerised and blended, the design space of this material class is very large. Figure 4 and Figure 5 show the most important thermal and mechanical properties of the PHA family with respect to other common consumer polymers.

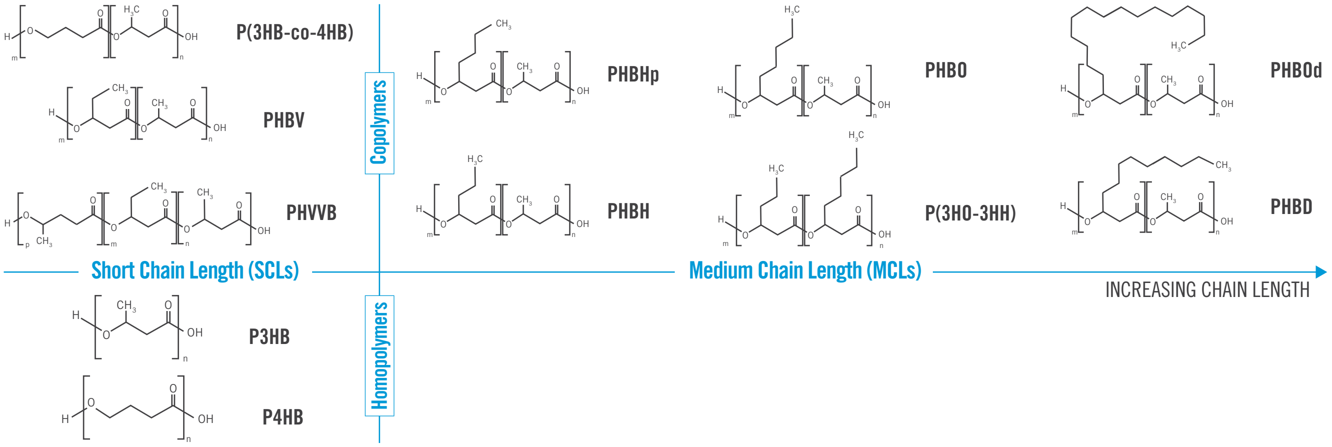

Figure 3: The PHA family

POLYMER CODE	POLYMER NAME	MATERIAL CLASS	PROPERTIES
P3HB	Poly(3-hydroxybutyrate)	Semi-crystalline thermoplastic	▪ Strong ▪ Brittle ▪ Small thermal processing window ▪ High softening temperature
P4HB	Poly(4-hydroxybutyrate)	Thermoplastic elastomer	▪ Strong ▪ Flexible ▪ Ductile ▪ High melt viscosity
P(3HB-co-4HB)	Poly(3-hydroxybutyrate-co-4-hydroxybutyrate)	Semi-crystalline thermoplastic/ thermoplastic elastomer	▪ Strong ▪ Tough ▪ Large thermal processing window ▪ Ductile
PHBV	Poly(3-hydroxyalkanoate-3-hydroxyvalerate)	Semi-crystalline thermoplastic	▪ Strong ▪ Brittle ▪ Large thermal processing window ▪ High softening temperature
PBHH	Poly(3-hydroxybutyrate-hexanoate)	Semi-crystalline thermoplastic	▪ Flexible ▪ Ductile ▪ Easy to process ▪ Low softening and melting temperature

Table 1: Summary of properties of some common PHAs

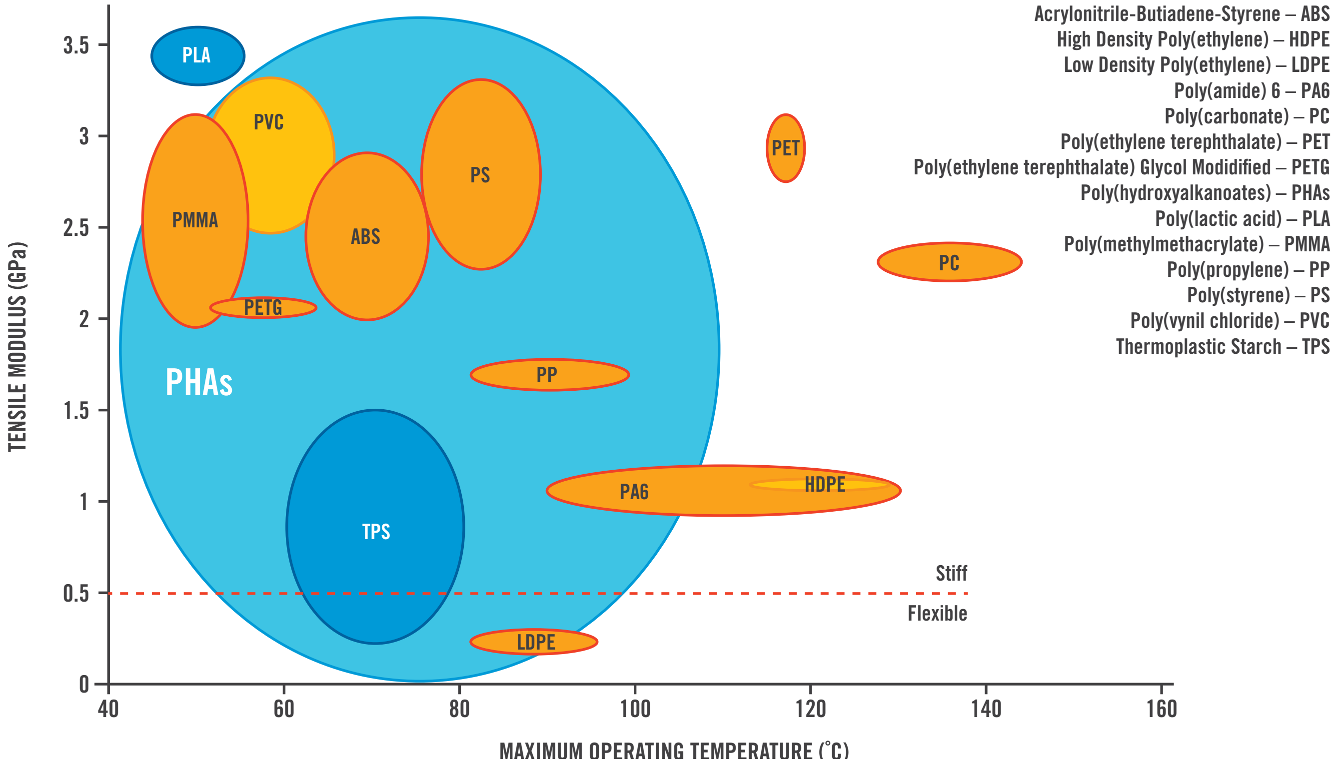

Figure 4: The PHA thermomechanical design space for stiffness (tensile modulus) against maximum operating temperature. Other oil based (orange) and bio based (blue) thermoplastic design spaces have been included for comparison

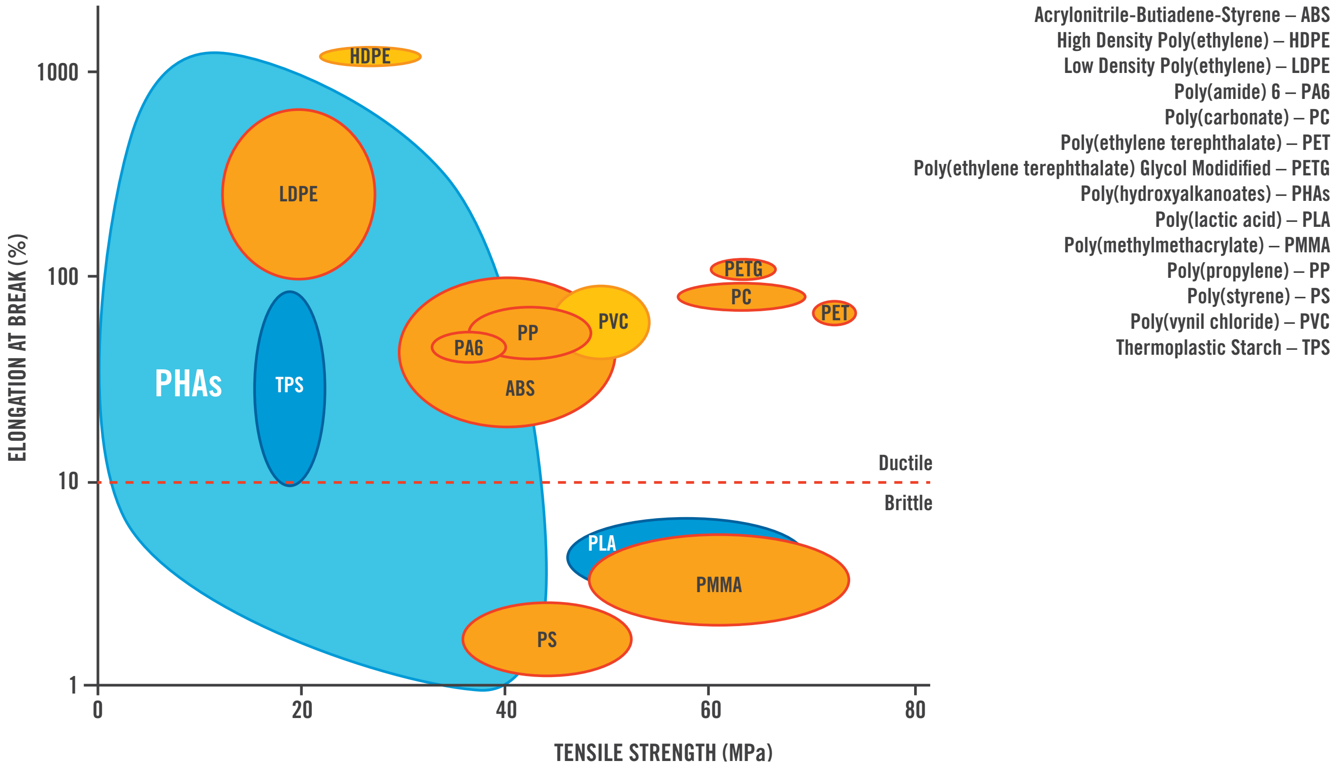

Figure 5: The PHA mechanical design space for elongation at break against tensile strength. Other oil based (orange) and bio based (blue) thermoplastic design spaces have been included for comparison

PHAS COULD SUBSTITUTE CONVENTIONAL PLASTICS IN A WIDE RANGE OF APPLICATIONS. END OF LIFE CONSIDERATIONS ARE AN IMPORTANT FACTOR IN DETERMINING WHICH APPLICATIONS ARE SUITABLE.

The versatility of PHAs lends them to a wide range of potential market applications. The main markets where PHAs have already achieved some degree of penetration are packaging, food service, agriculture and medical products. PHAs are penetrating in both low value, high volume markets (such as compost bin liners) as well as low volume, high value markets (such as absorbable surgical film). Figure 6 illustrates a number of the current and future applications of PHAs. A common misconception is that durable products cannot be made from compostable plastics. In fact, as we illustrate in Figure 7, compostable plastics can be suitable for manufacturing products with a range of life expectancies from disposable to products designed to last for a significant number of years such as automotive components and toys. PHA manufacturers are developing a diverse range of end markets, including environmental services, automotive, electronics and energy.

End-of-life considerations are important when considering which applications are suitable for designing with PHA. PHA products can either be designed to enter the natural environment (e.g. mulching films ploughed back into the soil) or to be treated in industrial composting facilities. Care must be taken not to contaminate existing recycling systems for conventional polymers; for this reason PHAs would not be suitable replacements for PET water bottles.

CURRENT		FUTURE
Refuse sacks, compost bin liners, carrier bags, gift bags, shrink wrap	PACKAGING	Bottles, laminate foils
Disposable gloves, disposable aprons, liners for coffee cups, foam packaging	FOOD SERVICE	Food containers and utensils
Mulching film, plant pots	AGRICULTURE	Slow release of fertilizers, etc. into soil
Absorbable sutures, absorbable mesh, absorbable surgical film, composite mesh	MEDICAL	Microencapsulation, slow release drug formulations, cartilage engineering, stents, wound dressings, bone plates, high performance filters, syringes, gowns, gloves
Phone case, furniture	CONSUMER PRODUCTS	Sanitary goods, wipes, textiles, toys, cosmetics (microbeads), interior design
Plastic additives	CHEMICALS	Adhesives, paints, coatings, fine chemicals
	ENVIRONMENTAL SERVICES	Oil slick remediation, denitrification (water treatment)
	AUTOMOTIVE	Automotive parts
	ELECTRONICS	Pressure sensors for heat sealing components, toner, electronic casings
	FISHING	Fishing nets and lures
	ENERGY	Fuels

Figure 6: Current and future PHA applications, by market segment

PHAS ARE ONLY AVAILABLE IN RELATIVELY SMALL QUANTITIES, FROM A LIMITED NUMBER OF SUPPLIERS AND LIMITED NUMBER OF CONTRACT MANUFACTURERS HAVE THE CAPABILITY TO PROCESS THEM.

Many bioplastic production plants are small compared to production facilities for conventional, petroleum-based plastics. For example, China's TianAn PHA plant has a capacity of approximately 2,000 metric tons per year — small by petrochemical industry standards. However, as bioplastics gain traction in various end-use sectors, a handful of producers have emerged as leaders in biopolymer production worldwide.

The thermoplastic nature of PHAs makes them ideal candidates for a wide range of standard manufacturing techniques including injection moulding, extrusion, film forming, melt coating and blow moulding. However, their relatively low thermal decomposition temperature (typically just above 180°C) means that careful processing and significant process development is usually required. This is particularly true for PHB, which has a melting temperature of 175°C.The non-trivial process development required for manufacturing with PHAs limits current outsourcing to contract manufacturers who have already developed a process for PHA manufacture. Although manufacture with PHAs currently presents a significant process development overhead for what still seems like a very niche market, interest is continuing to grow and the rewards for early adopters could well be significant.

NAME	LOCATION	TRADE NAME(S)	PHA TYPES	SCALE (TONNES PER ANNUM)	DEVELOPMENT STAGE
Newlight Technologies	US	AirCarbon™	PHB, PHBV, PHBH*	23,000 tpa	Commercial
Danimer Scientific (Meredian)	US	Nodax™	PHBH, PHBO, PHBOd	91,000 tpa	Commercial
Bio-on	Italy	MINERV-PHA	PHB, PHBVV	1000 tpa + licenced plants 5-10,000 tpa	Commercial
Tepha, Inc.	US	TephaFLEX®	P3HB, P(3HB-co-4HB), P4HB, P(3HB-co-3HV), P(3HO-3HH)	Unknown	Commercial
Ecomann / Shandong Ecomann Technology Co / Shenzhen Ecomann Biotechnology	China	Ecomann®	PHA + biopolymer blends, PHA + polyolefins blends, PHA/nanoclay composites, P(3HB-co-4HB), PHBV, PHBH*	5,000 tpa	Commercial
Biomer	Germany	Biomer	P3HB	1,000 tpa	Commercial
Tianan Biologic Material Co. Ltd.	China	ENMAT	PHBV	2,000 tpa	Commercial
PHB Industrial S.A, now Biocycle	Brazil	Biocycle B1000 B189C-1 B18BC-1 B189D-1	P3HB, PHBV	50 tpa	Pilot
Tianjin Greenbio Materials Co. Ltd	China	Sogreen	P(3HB-co-4HB)	10,000 tpa	Pilot
Mango Materials	US	N/A	PHB	Pilot	Pilot
Bioplastech	Ireland	N/A	MCLs	Research	Research
PolyFerm Canada, Inc.	Canada	VersaMer	PHBH, PHBHp, PHBO, PHBV PHBD, PHBDD (chain length mixtures)	Research	Research
Kaneka	Belgium	N/A	PHBH	Research	Research
Full Cycle Bioplastics	California	N/A	PHBV	Research	Research
Sirim	Malaysia	N/A	PHBV	Research	Research

Table 2: Summary of main PHA manufacturers. *Inferred from patents and/or literature

CAMBRIDGE CONSULTANTS HAS THE REQUIRED CAPABILITIES TO (RE)DESIGN PRODUCTS, ENGINEER BACTERIAL STRAINS AND EVALUATE MARKET APPLICATIONS FOR PHAS.

PHA bioplastics represent one example of many radical sustainable innovations which are decoupling business success from environmental impact. Cambridge Consultants works with multinational businesses to deliver step-change improvements in sustainability through cutting edge technology. The global bioeconomy is growing rapidly and Cambridge Consultants is fully invested in its future success, pursuing a wider strategy to introduce sustainable bioplastics into the product design toolkit, across a wide range of industries.

Using state-of-the-art facilities and techniques, our synthetic biology team fuses expertise in biology, chemistry and engineering to convert research-driven discovery into breakthrough products and services for industries as diverse as consumer products, healthcare and agritech.

Cambridge Consultants is uniquely positioned to provide:

1. Independent expert opinion on the market and technical potential of bioplastics in particular industries and applications

2. Product design or redesign to enable incorporation of PHA-derived materials, particularly for technically challenging applications

3. Synthetic biology to engineer industrial processes for PHA synthesis

Figure 7: Products that could be made from PHA. The items above include a variety of both consumable and durable products with very different physical and thermal requirements. All of the above items could be manufactured using the PHA family of bioplastics and would serve their intended design lifetimes. At end-of-life they could all be returned into the product life cycle by deliberate composting.

REFERENCED DOCUMENTS

This white paper is based on a full report "*PHAs: Market opportunities and technical possibilities*" written by Cambridge Consultants into the potential of PHA bioplastics. The full report is available to Cambridge Consultants' clients or potential clients on request.

About Cambridge Consultants

Cambridge Consultants is a world-class supplier of innovative product development engineering and technology consulting. We work with companies globally to help them manage the business impact of the changing technology landscape.

With a team of more than 750 staff in the UK, the USA, Singapore and Japan, we have all the in-house skills needed to help you – from creating innovative concepts right the way through to taking your product into manufacturing. Most of our projects deliver prototype hardware or software and trials production batches. Equally, our technology consultants can help you to maximise your product portfolio and technology roadmap.

We’re not content just to create ‘me-too’ products that make incremental change; we specialise in helping companies achieve the seemingly impossible. We work with some of the world’s largest blue-chip companies as well as with some of the smallest, innovative start-ups that want to change the status quo fast.

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For more information, or to discuss how this approach could fit your business, please contact:

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