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Conversion of Biomass into Bioplastics and Their Potential Environmental Impacts

Lei Pei[1], Markus Schmidt[1] and Wei Wei[2]
[1]*Organisation for International Dialog and Conflict Management,*
[2]*Institute of Botany, Chinese Academy of Sciences,*
[1]*Austria*
[2]*China*

1. Introduction

To build our economy on a sustainable basis, we need to find a replacement for fossil carbon as chemical industry feedstocks (Andrady and Neal, 2009). There are growing concerns about current petroleum based production, accumulation of waste in landfills and in natural habitats including the sea, physical problems for wildlife resulting from ingestion or entanglement in plastic, the leaching of chemicals from plastic products and the potential for plastics to transfer chemicals to wildlife and humans (Thompson *et al.*, 2009). Bioplastics, derived from bio-based polymers, may provide a solution. Unlike the chemically synthesized polymers, the bio-based polymers are produced by living organisms, such as plants, fungi or bacteria. Some microorganisms are particularly capable in converting biomass into biopolymers while employing a set of catalytic enzymes. Attempts to transfer biomass to produce industrially useful polymers by traditional biotechnological approaches have obtained only very limited success, suggesting that an effective biomass-conversion requires the synergistic action of complex networks. As an interdisciplinary research field which is a unique combination of life science and engineering, synthetic biology can provide new approaches to redesign biosynthesis pathways for the synergistic actions of biomass-conversion and may ultimately lead to cheap and effective processes for conversion of biomass into useful products such as biopolymers.

In the following sections of this review, we will give first an introduction on bioplastics and synthetic biology (section 2). The properties of bio-based polymers for bioplastics equal to or better than their chemical synthetic counter parts will be compared. The subfields of synthetic biology related to polymer biosynthesis will be reviewed. In the Section 3, we will focus on synthetic biological approaches to improve the biological system to produce polymers for bioplastics, such as polyhydroxyalkanoates (PHAs). The fourth section then goes on to evaluate the environmental impacts of the synthetic biology derived bioplastics. In this section, we will review the current methods to measure the environmental impacts on bioplastics on greenhouse gases (GHGs) emission, direct or indiret land usage, energy consumptions and waste management, as well as the current regulation guidelines on bioplastics in Europe. And in the last section, we will summarize the perspectives of synthetic biology and bioplastics.

2. Synthetic biology and bioplastics

Since industrialization, human beings have relied largely on chemicals derived from fossil carbon. Due to the unsustainable nature of petroleum and coal, it is essential to develop better alternatives to produce chemicals from renewable sources. The implementation of biological processing in industrial scale may help to reduce the undesirable damage to the environment caused by the massive scale productions from the current fossil fuel based chemical industry.

Among the commodity chemicals, polymers for plastics are becoming independent for our modern lifestyle (Andrady and Neal, 2009). Plastic have transformed our everyday life and their usage is increasing. Based on the report from Plastic EU 2009, the average annual increase of plastic production and consumption is 9% globally (PlasticsEurope, 2009). The plastic demand in EU was 48.5 million tones in 2008, of which 75% was composed by mainly five high volume families- polyethylene (PE), polypropylene (PP), polyvinylchloride (PVC), polystyrene (PS) and polyethylene terephthalate (PET). Majority of them are produced by chemical synthesis starting with petroleum feedstocks. These synthesized plastics are durable which make them resistant to biological degradation. Due to the toxic additives, for example, plasticizers like adipates and phthalate, burning plastic can release toxic pollutants. And the manufacturing of chemical industrial processes often creates environmental hazards. Due to the concerns over the climate change, limitation of the fossil carbon source and environmental mitigation, there are renewed interests in bioplastics.

There are mainly three types of bioplastics in the commercial scale of production (Table 1).

a. Plastics derived from fossil carbon source but biodegradable, and
b. Plastics derived from polymers converted from biomass and biodegradable, and
c. Plastics derived from polymers converted from biomass but not biodegradable.

In our current review, we will focus on the biodegradable, compostable and bio-based plastics. In our paper, we use the term 'bioplastics' only referring plastics made from this type of polymers.

Polymer	Company (example)	Scale (ton/year)
Biodegradable but not bio-based		
Synthetic polyesters	Ecoflex (BASF)	14 000
Polyvinyl alcohol (PVA)	Wanwei	100 000
Biodegradable and bio-based		
Starch based materials	Novamont	60 000
Cellulose based materials	Innovia Films	30 000
Polylactide (PLA)	Natureworks	140 000
Polyhydroxyalkanoate (PHA)	Metabolix (ADM)	50 000
Biobased but non-biodegradable		
PDO from biobased glycerol	Tate & Lyle (DuPont)	45 000
PE from Bioethanol	Braskem (DOW)	200 000 (planned)
PVC from Bioethanol	Solvay	360 000 (planned)
Polyamides (PA) from oils	Arkema	6 000 (planned)

Table 1. Polymers for bioplastics on the market (Kaeb, 2009).

The bioplastics available in the market are made from polymers such as starch-based, polyhydroxyalkanoates (PHAs), polylactic acid (PLA) and other polymers derived from renewable sources. Polylactic acid (PLA) is a type of thermoplastic polyester resulting from the chemical polymerization of the D- and L- lactic acids obtained from fermentation (Madhavan Nampoothiri *et al.*, 2010). Bioplastics made from PLA shows the similar properties as those made from petroleum derived polyethylene terephthalate polymer. Besides applications in plastics, PLA derived bioplastics are also used extensively in biomedical applications, such as sutures, stents, dialysis devices, drug capsules, and evaluated as a matrix for tissue engineering (Park *et al.*, 2008; Shi *et al.*, 2010; Shi *et al.*, 2009; Yao *et al.*, 2009). Polyhydroxyalkanoates (PHAs) derived plastics are considered as the best candidates to replace the current petroleum-based plastics due to their durability in use and wide spectrum of properties. The family of PHAs polymers is one of the most promising biodegradable materials to emerge in recent years. Up to date, there are more than 100 different monomers of PHA polyesters (Chen, 2009). The PHA monomers have been divided into two classes- short-chain-length hydroxyalkanoate (scl-HA, monomer of 3 to 5 carbons) and medium-chain-length HA (mcl-HA, monomer of 6 to 14 carbons) (Tsuge, 2002). Unlike other 'degradable' polymers such as those based on petrochemicals, PLA and starch polymers, PHAs have useful natural properties and, therefore, do not need to sacrifice their true biodegradability to improve their properties further. They have properties similar to those of PE and PP, ranging in properties from strong, mouldable thermoplastics to highly elastic materials to soft, sticky compositions. PHAs can be blended in the large number of copolymers which allow further engineer of polymers to the desired properties for a wide range of applications. Similar to those derived from PLA, PHAs have been used in a variety of biomedical applications such as sutures and surgical meshes. Polyhydroxybutyrate (PHB) is the simplest yet best known polyester of PHAs, which was first discovered as an intracellular biopolyester produced by the Gram-positive bacterium *Bacillus megaterium* (Lenz and Marchessault, 2005). PHB derived bioplastics are heat tolerant with a melting point at 175 °C. PHB is commonly used to make heat tolerant and clear packaging film. Since PHAs have many properties that are superior to those of PLA, there are more renewed interests in PHAs development (Chen, 2009). Thus, we will focus our review on the latest research on PHAs.

Bioplastics are currently only in a small portion (under 1%) of market share of plastics (EuropaBioplastics, 2011). In Europe, bioplastics on the market are defined as the plastics made from polymers according to standards (EN 13432). The polymers for bioplastics are usually produced in the biological fermentation processes using renewable and sustainable agricultural feedstocks, such as sugar, starch, oil, or lignocellulosic biomass. There are also non fermentative processes (thermochemical ones) in development to convert biological feedstocks to chemicals which have been reviewed elsewhere (Gong *et al.*, 2008; Gray *et al.*, 2006; Hames, 2009; Mu *et al.*, 2010). In addition, some of the polymers can also be produced directly *in planta* by industrial crops constructed via genetic modification (GM) routes (Matsumoto *et al.*, 2009; Poirier, 2001; Valentin *et al.*, 1999).

Up to date, most of the research on the production of biopolymers is at the concept or early research stage of development, while a few have been on commercial scales (Chen, 2009). Most of these polymers are manufactured via the microbial fermentation routes. A concept of a new branch of biotechnology termed white biotechnology, has been developed, referring to the industrial development and implement strategies for chemical production based on biomass-derived carbon sources (EuropaBio, 2003; Hermann and Patel, 2007;

Soetaert, 2007). Although the technologies were developed many years ago, large scale production of polymers from biomass was not feasible because those technologies were too expensive. However, in recent years, the innovations from the research sectors, particularly those on biotechnology, have made some of the biological conversions able to compete with the existing fossil based processes. To mention a few, there are productions of vitamins, antibiotics and ethanol using biotechnological approaches (DSM, 2004; EuropaBio, 2003; Hermann and Patel, 2007; Soetaert, 2007).

Applications	Examples	Reference
Medical applications	Production of anti-malaria drugs precursor in engineered yeast	(Ro *et al.*, 2006)
	Noval polio virus vaccine	(Coleman *et al.*, 2008)
	Controlling transgene expression in subcutaneous implants	(Gitzinger *et al.*, 2009)
Fuels & Energy	Non-fermentative pathways for synthesis of branched-chain higher alcohols as biofuels	(Atsumi *et al.*, 2008)
	Biological system as a template for photocatalytic nanostructures	(Nam *et al.*, 2010)
Chemicals	Synthetic protein scaffolds	(Dueber *et al.*, 2009)
	Improved production of glucaric aicid in engineered *E. coli*	(Moon *et al.*, 2010)
Biological computing	Synthetic oscillatory network of transcriptional regulator	(Elowitz and Leibler, 2000)
	Tunable synthetic mammalian oscillator	(Tigges *et al.*, 2009)
	Synchronized quorum of genetic clocks	(Danino *et al.*, 2010)
Organisms	Synthetic microbes	(Gibson *et al.*, 2010)
	Genetic modified insects for pest control	(Fu *et al.*, 2007)
Environmental applications	Arsenic sensor	(iGEM, 2006)
	Biosensors seek and destroy herbicide	(Sinha *et al.*, 2010)

Table 2. Achievements in Synthetic Biology

Synthetic biology (SB) has been considered as a new way of doing biotechnology. It is an emerging science and engineering field that applies engineering principles to biology. The potential benefits of SB include the development of novel medicines, renewable chemicals and fuels (Gaisser *et al.*, 2009). Due to the infancy of SB, a variety of definitions are circulating in the scientific community, and no consensus definition is drawn. SB-related research has been performed in several fields such as DNA synthesis (or synthetic genomics) (Carlson, 2009; Carr and Church, 2009; Gibson, 2009; Gibson *et al.*, 2008a; Gibson *et al.*, 2008b; Gibson *et al.*, 2010; Gibson *et al.*, 2009), engineering DNA-based biological circuits (Canton *et al.*, 2008; Endy, 2005), minimal genome (or minimal cell) (2009; Luisi, 2007; Mushegian, 1999; Wegrzyn, 2001), protocells (or synthetic cells) (Bedau *et al.*, 2009, Luisi, 2007) and xenobiology (or chemical synthetic biology) (Benner and Ricardo, 2005; Deplazes and Huppenbauer, 2009, Schmidt 2010). Among all these activities, engineering DNA-based biological circuits has contributed significantly to design advanced genetic constructs and to redesign biosynthesis pathways or fine tuned genetic circuits for biopolymer production. One of the notable examples of SB derived biological circuits is the

design of a metabolic pathway to produce a precursor of the anti-malaria compound Artemisinin, naturally found in the wormwood plant (*Artemisia annua*). The design and construction of this plant derived compound in engineered microbes, showed off the state of the art of enhanced metabolic engineering via SB (Hale *et al.*, 2007; Keasling, 2008; Martin *et al.*, 2003). A handful of successful circuits have been constructed to convert biomass to fuels and chemicals (Table 2). Besides working on practical applications, the research community also works on building so called standard biological parts (aka biobricks whereas 'biopart' is the technical expression) intending to rationalize and reduce the design complexity (Shetty *et al.*, 2008; Smolke, 2009). By building such bioparts, it would provide a useful set of well-characterized, pre-fabricated, standardized and modularized genetic compounds (such as sequences of DNA) for (re)engineering biological pathways with defined functions. If succeeded, these bioparts will provide useful elements to build up systems to execute the designed functions, such as microbial fermentation to brew new biopolymers for plastics.

3. Synthetic biological approaches to convert biomass to bioplastics

PHAs can be produced in almost all bacteria in the form of intracellular inclusions. In response to a certain deficient growth conditions, the biosynthesized PHAs can make up to 90% of the dry cell mass (Garcia *et al.*, 2004; Haywood *et al.*, 1990; Lee *et al.*, 1999; Madison and Huisman, 1999; Yim *et al.*, 1996). Some microbes in their wild type forms can already produce PHAs in sufficient quantity (ranging from 50% to 80% of the dry cell mass), such as *Rolstonia eutropha* (>80%), *Alcaligenes latu*s (>75%), and *Pesudomonas oleovorans* (>60%) (Chen, 2009). There are three well known natural biosynthesis pathways of PHAs (Tsuge, 2002). The pathway I is most common which is found in many bacteria. It leads to generate 3-hydroxybutyryl (3HB) monomers from acetyl-CoA derived from sugars while a set of enzymes are involved in this process, such as PhaA (3-ketothiolase which converts acetyl-CoA to acetoacetly-CoA), PhaB (NADPH-dependent acetocaetly-CoA reductase, resulting in 3-HB-CoA) and PhaC (PHA synthase, polymerizing 3HB-CoA to the final monomers). The pathway II and III are more commonly found in the genus of pseudomonas. They are pathways using either sugars or fatty acids as carbon source to convert to either acetyl-CoA or acyl-CoA, resulting mainly in mcl-(R)-hydrooxyacly (3HA) monomers. The (R)- specific enoyl-CoA hydratase (PhaJ) and (R)–3-hydroxyacyl-ACP-CoA transferase (PhaG) play similar roles as PhaB in the pathway I to obtain 3HA-CoA.

PHAs are truly natural polymers yet with properties similar to those of the synthetic ones. There is a renewed interest in producing PHAs in a biological process fed with sustainable sources. Several refactored microbes have been constructed to produce PHAs (Aldor and Keasling, 2003; Garcia, et al., 2004; Hofer *et al.*, 2010; Lee, et al., 1999; Li *et al.*, 2007; Park *et al.*, 2002; Qiu *et al.*, 2006; Sandoval *et al.*, 2007; Zhang *et al.*, 2009). One commonly used engineering strain is *E. coli*. Recombinant *E. coli* strains harbouring a set of PHAs biosysthesis genes (*phaCac* from *Aeromonas caviae, phaCABa1* from *Alcaligenes latus,* or *phbCAB* from *Ralstonia eutropha*) were constructed (Taguchi *et al.*, 1999). Sufficient amount of PHAs can be produced, while using sugars or fatty acids as carbon sources. Besides *E. coli*, *Aeromonas hydrophila* harbouring *phbAB* or *phaPCJ* were also constructed to produce PHAs using lauric acid as carbon source (Chen *et al.*, 2001). Some of the natural PHAs producing strains have been subjected to genetic modification to enhance their productivity. For instance, double knockout mutant of *P. putida* was generated using suicide plasmid bearing beta-oxidation genes *fadA* and *fadB*. The mutant strains produced more PHAs (84%) than its wild type strains (50%) (Ouyang *et al.*, 2007).

Based on these strains, a couple of biotechnology based fermentation processes have been developed for the industrial scale productions of PHAs (Chen, 2009). These fermentations are usually performed in two phases. The first phrase is a cell growth phrase to obtain high cell density and the second phrase is a PHA-production phrase of which cell growth deficient conditions are deployed in favour of the metabolic shift to PHA biosynthesis. To date, most of the PHAs production via microbial fermentations relies mainly on sugars and fatty acids as carbon sources (Chen, 2009). They are derived from the sustainable resources but with limitations while used in large scale. For instance, sugars are usually derived from starch (corn) that is also major food sources. Thus, PHAs produced by the current biotechnology processes are still far more expensive than those derived from fossil carbons. In order to make a biological based process compete with the traditional chemical processes, the PHAs will have to be produced at a higher yield preferably from a non-food biomass, more advanced PHA monomers with novel properties, less energy consumption and less green house gases (GHGs) emission while full life cycle analysis (LCA) is taken into consideration. It is highly expended that the novel approaches developed by SB may help to achieve these goals.

One of the contributions from SB is to develop better PHA production strains. Nearly all previous work using genetic engineering approaches has focused on reorganizing PHA biosynthesis genes derived from natural organisms. In contrast, SB will provide an integration of genetic engineering, metabolic engineering, chemistry and bioinformatics. For instance, using SB methods, microbes will not only harbour genetic circuits coding for PHA biosynthesis pathway, but also metabolic pathways which will enhance productivity. A research group of Tsinghua University has worked on such genetic circuits to enhance the production of PHAs in engineered microorganisms such as *E. coli*, *P. putida* and *A. hydrophila* (Jian *et al.*, 2010; Li *et al.*, 2010; Wei *et al.*, 2009). In order to convert lab scale fermentation to produce PHAs into the industrial scale, cells must be engineered to be able to grow in high density. It has been proposed that the limited oxygen supply is a hurdle that cells face while growing to high density. The problem was solved by constructing synthetic pathways that are turned on in response to micro- or anaerobic condition (Jian, et al., 2010). This approach has been also applied to produce poly-3-hydroxybutyrate (PHB) (Li *et al.*, 2009), which is currently produced from starch or glucose based feedstock by bacteria. The synthetic pathways were constructed to enhance PHB production from 29% to 48% of the cell dry weight under anaerobic conditions.

One of the key obstacles to produce renewable polymers by fermentations lies on the cost intensive downstream processing steps. A novel approach has been developed to remove this obstacle by equipping engineered strains with programmed autolysis genetic circuits. An inducing lysis system has been implemented in cyanobacterium *Synechocystis sp.* to facilitate extracting lipids for biofuel production (Liu and Curtiss, 2009). This inducible lytic system is composed of a lytic circuit from bacteriophage-derived lysis genes and an inducible circuit of genes encoding a nickel-inducible signal transduction system. If such programmed autolysis system is implemented in PHA producing strains, the efficiency of PHA fermentation will be increased.

To maximize the benefit of SB derived PHA production, it has been suggested to design producing strains to product PHAs with desired properties for applications of high added value. There were a couple of reports on PHAs with unusual properties, such as adding functional groups side groups to the PHA monomer mediated by low specific PHA synthases (Hiraishi *et al.*, 2006; Luengo *et al.*, 2003; Sandoval, et al., 2007; Tsuge *et al.*, 2005),

PHA monomer of high molecular weight by mutated synthases (Zheng *et al.*, 2006), and funtionalized PHAs containing C-C double bonds when fed unsaturated fatty acids (methanol) (Hofer, et al., 2010).

One of the key issues hindering the large scale biopolymer production is the cost of sugars and fatty acids as feed stocks. This issue is an obstacle not only to the production of PHAs but also other commodity chemicals and fuels. World food prices reached a record high recently, according to a report from the Food and Agriculture Organization (FAO) of the United Nations. The Food Price Index reached 214.7 points in December 2010 and slightly above the previous peak of 213.5 points during food crisis in 2008 (BBC News Bussiness, 2011). It has already been in debut that increasing biofuel production from starch and sugar may post further threat to the food safety. Thus, it is a key challenge to develop biological processes on how to harness the non-food biomass. In theory, cellulose biomass may be the best sustainable carbon source which could fill the gap left in crop supplies as stocks have been diverted for commodity chemicals (mainly biofuels) production. A great deal of work has been carried out to convert cellulosic biomass into useful products. It has been suggested by Christopher E. French that the ideal microbes should be equipped with a couple of properties such as the ability to hydrolyse cellulosic material effectively, with minimal requirement for pre-processing; the ability to convert the sugars released into molecules useful as liquid fuels and/or chemical industry feedstocks; self-tolerance to these molecules at a high concentration, and suitable respects for use in industrial bioreactors (French, 2009). Since such microbes are not known to exist in nature, they can be only constructed via complex engineering, something that SB is expected to be capable of. Most of the non edible biomass is made up by long cellulose fibres of hemi-cellulose and lignin (Lynd *et al.*, 2002; Lynd and Zhang, 2002). With respect to their chemical composition, hemi-cellulose is a mixture of monomers including D-xylose, L-arabinose, D-mannose and D-galactose, together with sugar derivatives such as 4-O-methyl-D-glucuronic acid. Lignin is a complex formed by polymerization of aromatic monomers. Such cellulose can be digested to D-glucose by enzymatic or non-enzymatic hydrolysis. A typical enzymatic hydrolysis of cellulose involves a multiple step process mediated by several enzymes. A handful of enzymes have been identified to degrade cellulose efficiently from different microbes (Lynd, et al., 2002), to mention a few, endogulcanases (enzymes able to cleave cellulose chains at random positions), exoglucanases (enzymes that move along the chain cleaving cellobiose residues from either the reducing or non-reducing end), and β-glucosidases (enzymes hydrolysis cellobiose to glucose). There is research on cellulosomes which are complexes of cellulolytic enzymes produced by bacteria (Bayer *et al.*, 1994). Cellulosomes can be used for the degradation of cellulose and hemicellulose, and they have in fact been considered as one of nature's most elaborate and highly efficient nanomachines (Fontes and Gilbert, 2010). Integration of cellulosomal components occurs via highly ordered protein-protein interactions between two proteins: cohesins and dockerins, which specificity allow the incorporation of cellulases and hemicellulases onto a molecular scaffold. Cellulosomes can be used for a range of SB applications, from clothes whitening to paper waste treatment or chemical production from lignocellulosic biomass, and the first synthetic cellulosomes have already been constructed (Mitsuzawa *et al.*, 2009). SB will play an important role in developing cellulose degradation module along with the chemical producing module where the standardization of biological parts and interdisciplinary nature of SB enable combination of multiple modules. As it has been mentioned above, SB approaches could create artificial enzymes that are tailored for enzymatic activities that do not exist in nature. To date,

degradation of lignin and cellulose is still problematic though they can be degraded by enzymes produced by very few fungi. Using SB methods may develop lignin degradation enzymes with enhanced capability and that do not exist in nature. In addition, one possible solution is to make the biomass easy in hydrolysis such as the biomass from genetic modified plants. Such attempt has been tried by lignin deficient genetically modified plants (Baucher *et al.*, 2003). The same idea has been applied to develop genetically modified potatoes for industrial applications which have been approved to cultivate in EU (Ryffel, 2010). Thus, no doubt, biomass with properties that is more suitable for industrial scale of fermentation will be developed as well.

4. Environmental impacts of synthetic biological production of bioplastics

The plastics made from fossil derived synthetic polymers have posted serious problem for environments (Thompson *et al.*, 2009). Each year, millions tons of synthetic plastics discarded and less than one tenth has been recovered and recycled. Majority of them are end up in landfill or enter the natural habitats (waters and surface land) (Hopewell, et al., 2009). Some disposed synthetic plastics can remain in the environment for up to thousands of year (Andrady, 1994).

Furthermore, the predicted depletion of fossil fuel resources, the building up landfill of plastic waste and the implementation of low-carbon environmental protection initiatives call for an intensive search for alternatives to synthetic plastics (Prieto, 2007). Bioplastics may offer benefits relative to fossil-based plastics, particularly environmental benefits. Today bioplastics have been considered as a better solution to the increasing demands for truly sustainable growth. In developing the new generation of plastic products made from renewable feedstock, the ability of biodegradability, compostability and the evaluation measured by Life Cycle Analysis (LCA) should be all taken into account to evaluate the contributions to the environmental impacts of bioplastics.

Biodegradability is the ability of organic substances and materials to be entirely converted into simple inorganic molecules such as water, carbon dioxide and methane through the biological processing mediated by microbial enzymes (Novamont, 2011a). Such a processing is part of the natural life cycle of carbon recycling of the earth. Ideally, organic waste from human activities should be removed through biodegradation to minimize their impacts to nature. It is critical to identify the key components in this processing to reach maximum efficiency. As it is known, it takes different time to biologically degrade different types of organic waste, for instance, straw and wood take longer than starch and cellulose. This implies that biodegradation is strongly influenced by the chemical nature of the substance or material to be biodegraded. To facilitate the processing, the industrial biodegradation has been used to process the urban waste. It occurs at a consistent step of composting and anaerobic digestion. Composting will produce mature compost which turns into a fertiliser, while anaerobic digestion followed by stabilisation through composting will produce biogas.

Compostability is the capacity of an organic material to be transformed into compost through the composting process (Novamont, 2011b). Composting can be conducted at a small scale such as home-hold composting bin, or at an industrial level. The production of compost and its use in agriculture represent the closure of the environmental cycle and constitute a simple way to address the problem caused by the removal of organic substances from agricultural soils, reduced soil fertility and the onset of desertification. Composting is

currently applied to selected waste that only contains biodegradable organic matter where the traditional plastics are not included in composting because they resist to the biodegradation. In contrast, biodegradable plastics can be included in composting, but only if they satisfy the criteria established by the standards that define compostable materials. Incompatible materials were composted in the past in the absence of rules and in a context of unregulated definitions and test methods. This caused significant damage, not least to the trust of users and technicians responsible for composting facilities. Bioplastics that comply with these standards can play a fundamental role in the valuation and optimisation of the composting process and in the production of high quality compost.

Bioplastics, particularly those made from PHAs are truly biodegradable. PHAs can be broken down into carbon dioxide and water by hydrolysis and microbial fermentations. PHAs-degrading enzymes have been identified in some bacteria and fungi, termed depolymerises (Elbanna *et al.*, 2004; Jendrossek and Handrick, 2002; Kim do *et al.*, 2007; Tokiwa and Calabia, 2004). PHAs degrading microorganisms can be enriched from samples collected from various ecosystems where PHAs have been supplemented as a sole source of carbon and energy. There are mainly two types of such microbial degradation- extracellular and intracellular ones (Jendrossek *et al.*, 1996). Besides using the native PHAs degrading strains, an advanced PHAs degrading system may be built up using the SB methods, for instances, better deploymerases or fermenting strains (Knoll *et al.*, 2009). With more knowledge accumulating on the biodegradation of PHAs, we may expect that plastics made from polymers - which are easy to be broken down - will have more applications in the future. We also need to point out that not all bioplastics will degrade to the same extent in the anaerobic digestion step and they may perform differently in the different technologies. For this reason more research is needed on the behaviour of different bioplastics in different anaerobic systems. In addition, it has been suggested that the anaerobic fermentation on bioplastics may be combined with the production of biogas because bioplastics are carbohydrates with little or no nitrogen and therefore with a high C/N ratio, making them more suitable for energy generation during fermentation than the traditional organic waste (urban organic waste, agricultural waste, etc). SB derived degradation processes that enable the combination of degradation and energy generation will maximize the benefits of bioplastics further.

Life Cycle Analysis (LCA) has become essential in evaluating the environmental impact of a product (Novamont, 2011c). It is a method for evaluating and quantifying the energy and environmental consequences and potential impacts associated with a product/process/activity throughout the entire life cycle, involving the assessment on the entire product chain ("from cradle to grave"). Evaluations on the feedstocks, their production, use and end of life in the same context have enormous potential for many biomass derived products, particular biofuels and chemicals like bioplastics. To assess the non-renewable energy consumption and greenhouse gas emissions of PHB, the environmental performance of PHB derived from corn grain was evaluated through LCA (Kim and Dale, 2008). It showed that corn derived PHB offers environmental advantages over fossil polymers- with less non-renewable energy consumption (95% reduction) and less greenhouse gas emissions (200 % reduction) as compared to the petroleum-based plastics. Calculating the overall environmental benefits, particularly on GHGs and energy saving, attributed to lignocellulosic biomass derived products is challenging because whole production chains are complex. It can be expected that different approaches and interpretations on LCA will provoke a debate about the environmental merit of bioplastics.

A recent study on biofuel converting from lignocellulose conducted by Slade et al. showed that the most important factors affecting GHGs emission are the emissions from biomass production, the use of electricity in the conversion process; and from the potentially consequential impacts: (in)direct land-use change and fertiliser replacement (Slade *et al.*, 2009). GHGs from land use change (the so-called "carbon debt") is one of the major contributors to the environmental impacts of biomass derived products. The GHGs of biofuel was studied, and it showed the time required for biofuels to overcome the potential carbon debt and begin providing GHGs benefits would be 100-1000 years depending on the ecosystem that was replaced. Thus, using crop biomass as feedstocks for chemical productions may take a long time to gain environmental benefits from the carbon debt. Using non-crop biomass, such as lignocelluloses, may maximize the environmental gains. Furthermore, there is ongoing research on using other inexpensive carbon sources for bioplastics productions. For example, xylose which is one of the abundant sugars in food industrial waste can be converted to lactic acid and acetic acid by an anaerobic fermentation. They can subsequently be used as feasible feedstocks for PHA production (Tsuge, 2002). Eventually, carbon dioxide would serve as an ultimate source for PHA production (Tsuge, 2002). It is known that several research groups are working using SB methods to engineer photosynthetic organisms (cyanobacteria or micro algae) that can catch carbon dioxide directly and convert it to biofuels (Fischer *et al.*, 2008; Rosenberg *et al.*, 2008). The same techniques can be applied to implement the PHA synthesis pathways instead of the ethanol or fatty acids synthesis pathways in the engineered microbes.

One important problem will arise: should synthetic biology be able to help solve the above technical issues, namely that more and more agricultural land will be devoted to plant energy-crops instead of food crops. In order to avoid such competition with food, we suggest also using non-food-competing biological resources such as perennial plants grown on degraded lands abandoned for agricultural use, crop residues, sustainable harvested wood and forest residues, double crops and mixed cropping systems, as well as municipal and industrial organic wastes.

Besides the potential environmental benefits of bioplastics, it is worthwhile to point out another benefit of bioplastics due to the biological processing in their industrial productions. From this perspective, SB based techniques have the potential to avert the use or by-product of toxic molecules in the production process (DSM; EuropaBio, 2003; Hermann and Patel, 2007; Schmidt and Pei, 2011; Soetaert, 2007). While these productions will be at bulk chemical scale, the environmental impacts will be marked- less pollution releasing to the environment, less processing cost on industrial waste and etc.

As it mentioned above, the synthetic plastics have been entered into the environment in large quantity since the last half century. And plastics are now one of the most common and persistent pollutants. Besides replacing synthetic plastics with more environmental friendly bioplastics which are degraded and compost, SB based techniques may provide new solutions for the already existing plastic waste- new approaches to break down the chemicals which are difficult to degrade and take long time. Microbes using synthetic polymers as substances might be created although there are none existed in nature. However, the consequences of the environmental leakage of the engineered plastic-eating microbes that could degrade plastic would be serious and the research should be subjected to thorough considerations (Collins, 2008).

The current legislation on bioplastics in the EU has been focused on sustainability, carbon footprint, and labelling. The European Directive 94/62 EC and Directive 2004/12/EC

provide reference to European standard (EC Packaging, 2004). The EN 13432 defined the biodegradable and compostable polymers as that the plastics made from at least 90% of the organic material must be converted into CO_2 within 6 months. Directive 2004/12/EC on Packaging & Packaging Waste specifies what bio-based products are. Further more, the EU environmental regulations played a role in providing incentives for the emergence of the bio-based product market. There are different rationales in supporting the R&D in bioplastics. For the industrial stakeholders, bioplastics have high market potential. For the agricultural stakeholders, bioplastics will be a new market potential for agriculture derived raw materials. For the environmental protective agencies, bioplastics might contribute to reduce the so-called carbon footprint. At the national level, some countries (for instance, Germany) set specific targets, e.g. that the more than 75% of the packaging should be from renewable sources (the Federal Environment Ministry Germany, 2009).

5. Conclusion

Bioplastics, defined as plastics derived from renewable carbon sources that are also biodegradeable, have been considered as good candidates for sustainable development as well as eco-friendly environment. The R&D on SB approaches is highly expected to deliver feasible approaches to bulk production of bioplastics. There are many aspects where SB can contribute to obtain this goal (Figure 1). Both SB and bioplastics are in their early stage of development. Most of the SB related research on bioplastics is focused on improving production of PHAs. More matured processes for large-scale conversion of biomass to

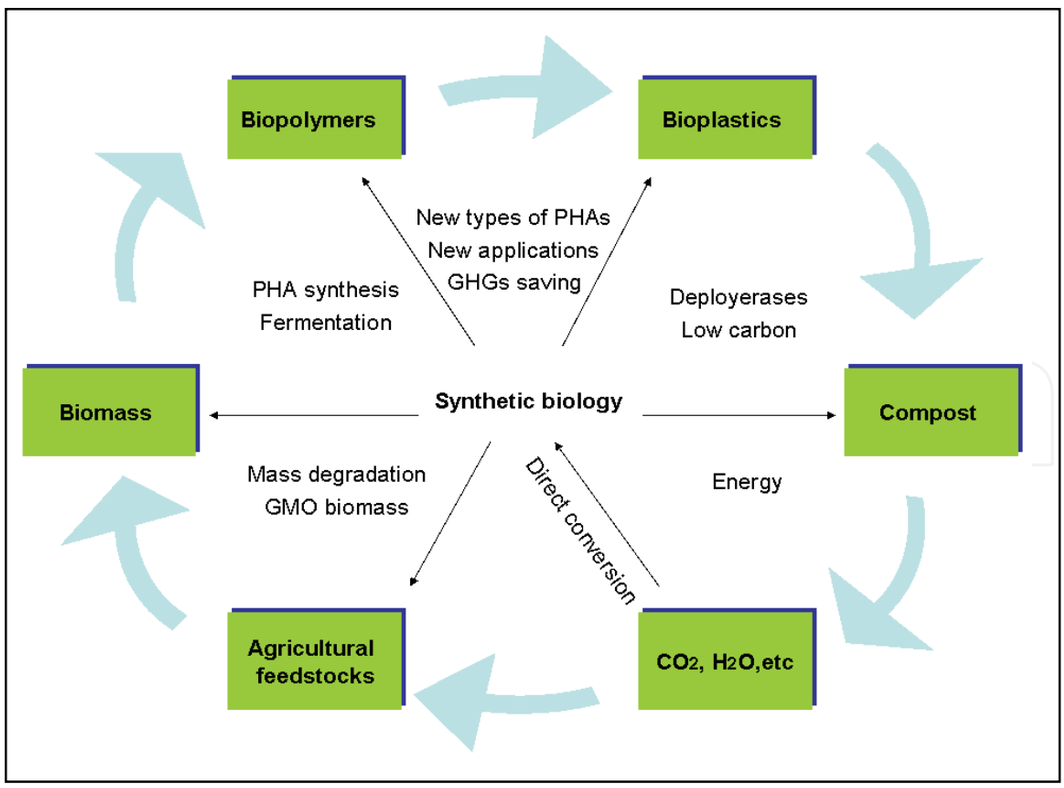


Fig. 1. Synthetic biology, Bioplastics and Environment.

polymer by SB design approaches could significantly influence the bulk production of bioplastics. However, adoption by industry on a new biological processing is expected to be slow, even though there are clear benefits on environmental perspectives over the long-term. Regarding to the market potential of bioplastics, the incentives and subsidy from the legislation body are currently the main driving force of the R&D of bioplastics and have high influence to the marketing of the end products. Bioplastics derived from lignocellulosic sources hold promise for emission reductions yet the techniques in harnessing lignocellulosic biomass is at the development stages. If the techniques become feasible, it will make the feedstock price of bio-based products lower and competed with those of fossil sources. Designer polymers with new properties will broaden the application of bioplastics-not only in packaging (currently), but also in other applications (medicine, textile, electronics etc). Improvements in biodegradation of bioplastics particularly combining with energy generation will make the benefits maximized.

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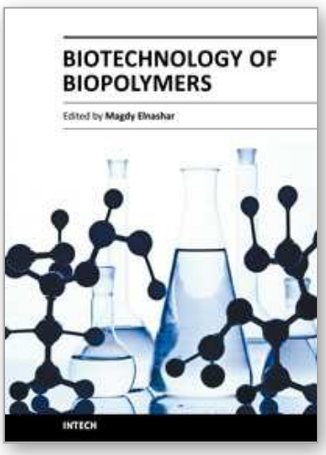
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The book "Biotechnology of Biopolymers" comprises 17 chapters covering occurrence, synthesis, isolation and production, properties and applications, biodegradation and modification, the relevant analysis methods to reveal the structures and properties of biopolymers and a special section on the theoretical, experimental and mathematical models of biopolymers. This book will hopefully be supportive to many scientists, physicians, pharmaceutics, engineers and other experts in a wide variety of different disciplines, in academia and in industry. It may not only support research and development but may be also suitable for teaching. Publishing of this book was achieved by choosing authors of the individual chapters for their recognized expertise and for their excellent contributions to the various fields of research.

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InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821

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