Nanotechnology for Biodegradable and Edible Food Packaging

Special Interest Report
for the ObservatoryNANO

2010

This special interest report is designed to be a quick reference text on the major elements of nanotechnology developments for biodegradable and edible food packaging. Identified as a an area of special interest in the 1st year of the ObservatoryNANO project

The target audience for this report includes policy makers, funding agencies and other interested parties.

For more detailed information on the technologies or products referred to in this report, please consult the online resources which provide in-depth analysis of Science and Technology developments and Economic developments, or get in touch with the specific points of contact:

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Food Packaging Trends – new functionalities and greener products

An evolving food packaging sector – opportunities for nanomaterials?

Historically, packaging has been developed to protect food from heat, light, moisture, oxygen, microorganisms, insects and dirt. Food preservation has also been a key requirement. In the past few decades we have seen an increase in the required functionalities of prolonging the shelf life of foods by controlling microbial, enzymatic and biochemical reactions of the internal environment of the packaging via a number of strategies such as oxygen removal, controlled release of salts, carbon dioxide etc.

Other drivers alongside food protection/preservation include containment and waste reduction, convenience packaging, traceability and tamper indication. These requirements for broader functionality have provided the stimulus for a number of fields of material development:

- Advanced food contact materials (FCMs) incorporating nanomaterials to improve packaging properties such as temperature and moisture stability, flexibility, barrier properties etc.;
- Active packaging (internal environment control including interacting with food contained within); and
- Smart packaging (including functionalities such as trace & track and indication of authenticity)
- Biodegradable packaging materials

Nanotechnologies offer promising innovations for these broad functional requirements. In particular, nanocomposites promise enormous potential for a number of these, and we are seeing the first products on the market. Examples of products include Imperm® for CO_2 release reduction (Nanocor® Inc), Aegis® OX a barrier nylon resin for oxygen scavenging (Honeywell) and Durethan® KU2-2601 (Bayer AG) for enhanced barrier properties. Examples of biopolymer based nanocomposites include NanoBioTer® and Degradal® (in development) which incorporate nanoscale additives for controlled or accelerated compostability and biodegradability.

The ObservatoryNANO has reported on all four of these broad functionalities (see www.observatory-nano.eu); however, of these one particular area is attracting particular interest, that of nanotechnology enabled bio-based[1] polymers[1] for biodegradable packaging and edible films. The area of bioplastics is garnering increasing interest due to improved processing and the potential of advanced composites. The field is driven by factors including:

- **High cost of fossil fuels:** Although there are clear environmental and sustainability benefits of bio-based polymers, it is the rising prices of crude oil and natural gas that are driving the economic based assessment. This, in line with the other two driving forces (outlined below) may provide the impetus needed to make a transition to bio-based plastics.

[1] These are defined as man-made or man-processed macromolecules derived from biological resources and for plastic and fibre application.

- **Waste Management:** This encompasses new initiatives for the decrease in agricultural waste (or finding novel uses for it), for example Europe's fruit and vegetable industries generate about 30 million tonnes of waste a year[2]. Another example is the recent move by the UK Government who stated that that in 10 year's time, 75 per cent of all household waste should be recycled, *"Early next year we will consult on what recyclable and compostable items should be banned from landfill and how a ban will work,"* said a statement from for Environment, Food and Rural Affairs (Defra).
- **Environmental sustainability and Agricultural management**: As with all industries, there is pressure to be both environmentally, and economically, sustainable in the long term. Therefore there is a drive to create renewable materials, and agricultural based materials hold promise.

Why is this dubbed a topic of special interest by the ObservatoryNANO?

Through the activities of the ObservatoryNANO we have seen that nanotechnologies, and in particular nanomaterials, promise solutions to some of the performance issues of bioplastics for food and drink packaging purposes. Improved functionalities and novel packaging concepts are enabled by advances in nanomaterial research and processing technologies. This means that natural polymers, such as sugars and proteins, can be combined with nanoclay and bio-based nanomaterials (such as cellulose nanofibres) to create potentially non-toxic, biodegradable and biocompatible materials – which some have dubbed as "green nanocomposites".[3]

However, the combination of nanomaterials with bioplastics (for the remainder of this report we shall use the term biopolymer) brings with it new technical challenges as well as waste management and regulatory issues. This report will provide an analysis of the nanotechnology research underway in this domain and identifies some of the economic, regulatory and environmental issues, and opportunities surrounding nano-enabled biopolymer packaging innovations. This should provide a first entrance point to the assessment of this domain and enable a more effective benefit/risk analysis.

Introduction

Definition

Food packaging and distribution for the purpose of this report is defined as materials used to package fresh and processed foods, and the procedures and systems in place to monitor supply chains and authenticate items.

Methodology

The data gathering approach for this report has been structured along three lines with three methodologies.

Three lines of investigation:

(1) Scientific and Technological Developments;

(2) Market and broader economic factors; and

(3) Other framing conditions that will affect innovation such as regulation, standards, environmental, health and safety issues (EHS), and societal issues.

Together these provide a multi-faceted but integrated investigation into the challenges and opportunities in this area, providing relevant input in line with the elements set down in the EU Action Plan for Nanosciences and Nanotechnology[4] and the proposed European Code of Conduct for responsible nanoscience and nanotechnology research.[5]

The three methods used:

(1) Literature and patent analysis;

(2) Interviews; and

(3) Focus workshops[2].

This integrated analysis brings together technology and economic assessment along with indications of the drivers and barriers, boundary conditions, market factors, regulatory issues and societal aspects, along with profiles of selected companies and products.

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[2] This report uses evidence and insights gained from an interactive workshop held in Dusseldorf on 10/03/2009 entitled: Advanced and Active Nanomaterials for Food Packaging:
Evaluating Technology Maturity and Innovation Chain Readiness. It also uses feedback and interactions from a conference in which ObservatoryNANO findings were presented at the workshop: 3rd International Active Packaging and Intelligent Packaging Conference - 1-2 April 2009 – Campden BRI, UK.

Science and Technology aspects

Bioplastics as an important innovation area for Europe

In its recent report entitled "World Bioplastics to 2013", Freedonia[6] predicts that the global demand for bioplastics will rise more than 400% mainly due to high crude oil and gas prices. Other important factors include: consumer demand for more environmentally sustainable products; the increased production of certain bioplastics; notable polylactic acid (PLA); and political and regulatory pressure to reduce non-degradable plastics. Of course, there are non-biodegradable bioplastics options, and the Freedonia report identifies that the fastest growing sector in bioplastics will be non-degradable plastics – predicting a rise in demand from 23,000 tonnes in 2008 to nearly 600,000 tonnes in 2013. However, other pressures are building, stemming not from the plastics industry, but from waste management. For example, there are increasing pressures from governments for restricting the types of waste to be deposited in landfill sites, heightening the need for alternative waste management.[7]

Another recent study by the industry bodies European Bioplastics and the European Polysaccharide Network of Excellence is in line with the Fredonia report, noting the strong link of growth of bioplastics to the price of crude oil and natural gas. Some major bottlenecks that this report gives include issues such as the performance of some bio-based plastic materials, their relatively high production and processing costs, as well as the need to minimise use of agricultural land and forest.[8] Similar to concerns surrounding the debate on biofuels, they predict a land management problem of competition with food production along with a need for consideration of the environmental effects of large scale bioplastics industry.

Europe accounts for approximately 40% of global demand for bioplastics, driven by consumer demand, regulatory pressures for greener packaging options, and a growing composting infrastructure. [9]

State of R&D

An introduction to nanocomposites

Nanocomposite materials employed, or being developed for use, in the food packaging industry contain a polymer plus a nano-additive. Mostly nanoclay particulates are used; however, other composites containing nanoparticles, nanotubes or nanofibres are also being developed. We can broadly divide the types of polymers into petrochemical based and bio-based polymers in the following way.

> **Petrochemical based polymers:** Most polymer composite materials are based on fossil fuel derivatives. Polyamides, nylons, polyolefins, polystyrene, ethylene-vinylacetate copolymer, epoxy resins, polyurethane, polyimides and polyethylene terephthalate . Examples of petrochemical based nanocomposites already on the market include Imperm® for CO_2 release reduction (Nanocor® Inc), Aegis® OX a barrier nylon resin for oxygen scavenging (Honeywell) and Durethan® KU2-2601 (Bayer AG).
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> **Biopolymers**: Research into biopolymers (sourced from wood and crop waste) is offering biodegradable alternatives. Such biopolymers include: Polysaccharides (such as cellulose and chitosan); proteins; lipids; and their composites. They have other advantages since biopolymers are excellent vehicles for incorporating a wide variety of additives. On their own biopolymers have poor mechanical properties (for example lipids) or poor water vapour barrier properties (for example polysaccharides). This has meant little uptake industry. However, addition of nanotechnologies may help here. These are emerging; NanoBioTer® has gained regulatory approval and Degradal® is in development.

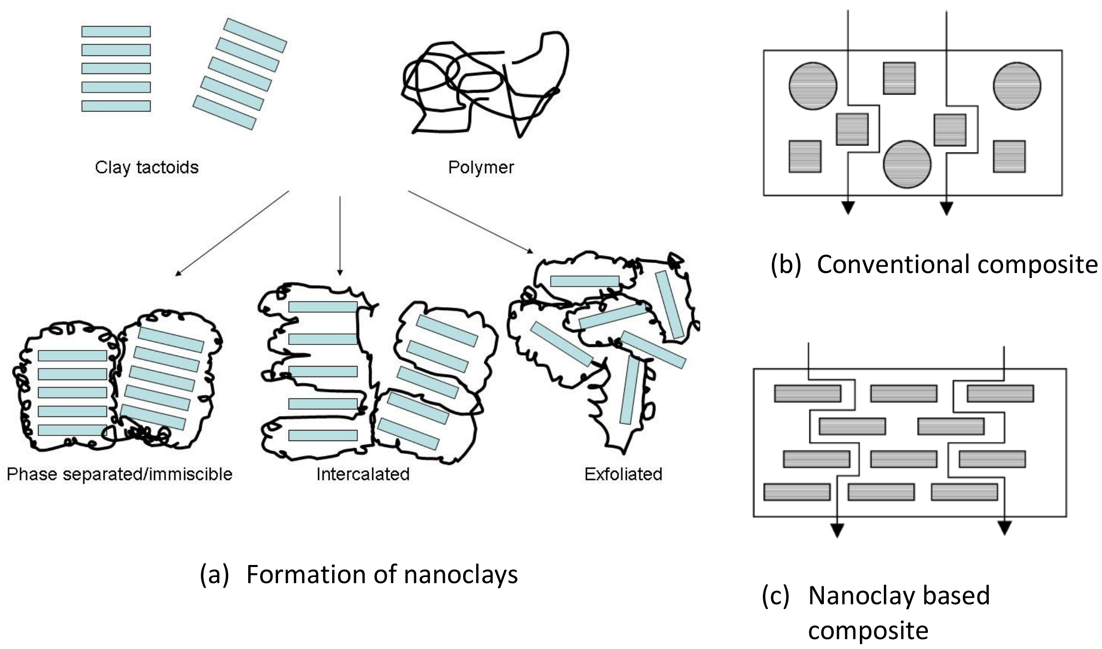

Figure 1 *(a) shows the creation of clay nanocomposites, which are the dominant form of nanocomposites on the market today, (b) we see the conventional path of gas through a polymer based composite, (c) shows the increased tortuous path created by nanoclay composites which helps in reduction of gas transport. (Adapted from Rhim et al., 2007[1]).*

Nanomaterials, other than nanoclays, include metal and metal oxide nanoparticles, carbon nanofibres and nanotubes, and nanofibres and nanotubes of other materials, including biomolecules. For example, DuPont are marketing a titanium dioxide nanoparticulate (Light Stabilizer 210) to block UV light and provide a longer shelf-life for food (this is currently before the US regulatory authorities for use in non-contact food packaging materials); and Rohm and Haas are marketing acrylic nanoparticles (Paraloid BPM-500) to increase the strength of polylactic acid, a biodegradable polymer.

Nanocomposites hold promise as they offer improved functionality over traditional composites and polymers in terms of barrier properties, strength, elasticity and optical clarity. Nanocomposites can be functionalised to include other characteristics such as antimicrobial activities, visual indicators of food freshness, means of identification, and possibilities which augment the ease of tracking. Another desirable property is sustainability. Most polymer composite materials are based on fossil fuel derivatives; however research into biopolymers (sourced from wood and crop waste) is offering biodegradable alternatives. The inherent drawbacks of pure biopolymers, which dependent on type, can include poor barrier properties or poor mechanical properties, can be mitigated by the inclusion of nanotechnology to form nano-enabled biocomposites (bionanocomposites). Most nanocomposite materials employed, or being developed for use, in the food packaging industry contain nanoclay particulates; however, other composites containing nanoparticles, nanotubes or nanofibres of metals, metal oxides, biopolymers[10],[11],[12] or other carbon-based materials are also being developed.

Virtually all polymers used in food packaging are thermoplastic, rather than thermoset. As such they can be melted after use and re-moulded into another product. Issues arise, however, when different polymers are utilised within one product, requiring mechanical separation before re-use.

Moving on from this broad introduction to nanocomposites, we will describe some of the research and development activities in three areas;

(1) bionanocomposites

(2) bio-based nanofibres

(3) edible films

There is technological overlap between these three sub-groups; however, there *are* clear distinctions between the three when looking at their applications, the manufacturing process, and the environmental, health and safety aspects. These will be covered later in the report. This report focuses on biodegradable plastics defined as biopolymers in which at least one step in the degradation process is via metabolism by naturally occurring organisms.

Bionanocomposites

For many plastics recycling is made difficult as a result of the different components involved, which means that the item cannot be processed in a single step, but needs to be dismantled and component plastics separated. One way to avoid this, but to still achieve sustainability, is to use biodegradable polymers from renewable sources. These are generally proteins or carbohydrates and can be derived from animal or plant origin. Lipid films can also be created but these tend to be used to directly coat and protect foodstuffs.

Polylactic Acid (PLA) is widely seen as the biopolymer with the highest potential for commercialisation, mainly due to its ease of production from carbohydrate feedstock such as maize, whey, wheat, or molasses. Polyhydroxybutyrate is another interesting biopolymer for industrial applications; it is highly crystalline and low water permeability. However, in its pure form it has an unfavourable ageing process. Both of these promising biopolymers have limitations due to some deficient functional properties, which can potentially be mitigated through the creation of bionanocomposites.

When biopolymers (such as cellulose) are mixed with nanoclay particles, the resultant nanocomposites exhibit improved barrier properties compared with the pure polymer, and after their useful life can be composted and returned to the soil[13]. Other nanomaterials can be used including metal oxide nanoparticles, and carbon nanofibres and nanotubes.

Other biopolymers that have been combined with nanoclays include chitosan, starch, casein, whey, and gelatine[14]. Soy protein has also been garnering interest due to its biodegradability characteristics and its thermoplastic properties. Limitations include brittleness and poor moisture barrier properties and thus plasticizers and reinforcements need to be added.

The potential applications vary from stand alone barrier films to coatings on other polymers and paper based packaging, to direct coating of foodstuffs.

Such biodegradable nanocomposites could be of great use in other agrifood application areas, such as the plastics used in agriculture (polytunnels, wrapping for feed, wrapping for hay, etc) that are either disposed of into landfill or burned by farmers (estimated to be on the order of 6.5 million tonnes[15] per annum). Instead of incineration, they could be composted and returned to the soil.

The main considerations when using natural polymers are that they often have poor mechanical strength, and are permeable to water. As with other nanocomposites, significant research still needs to be undertaken to determine how properties can be best enhanced for specific applications through the use of different nanoparticulates, plasticisers (some biopolymers, such as starch, are not thermoplastic), and melt conditions.

More will be described regarding bionanocomposites in the section on edible films. The following section describes another way of forming biobased nanomaterials, electrospun nanofibres, which promises improved functional properties in comparison to bulk biopolymers.

Bio-based nanofibres

In addition to melt extrusion, many biopolymers such as chitosan, cellulose, collagen and zein (derived from corn) have been synthesised as nanofibres using high electrostatic potentials from various biopolymers via the electrospinning technique[16], [17], [18]. In some cases these have superior properties to the traditionally cast polymer, including increased heat resistance[19,20], and additionally mats of such nanofibres possess a highly nanoporous structure and can be used as support matrixes for additional functionality.

Zein is a promising biopolymer for packaging purposes due to its strong hydrophobic characteristics, or in other terms water resistance. In addition zein has good mechanical properties in nanofibre form via electrospinning of zein[21] , [22]. Zein has also been widely studied for toxicity, and its non-toxic characteristics have enabled its uptake as a coating material in the pharmaceutical industry[23]

Another interesting and widespread biopolymer is chitosan obtained through deacetylation of chitin which can be found in crustaceans and a large number of insects. It has a number of attractive properties, when modified, for food packaging such as antibacterial action[24]. Unlike zein, due to its polycationic nature in solution, electrospinning is particularly challenging.

An interesting approach of electrospinning blends of zein and chitosan has been reported in 2009. These blends are reported to have great potential for application in active and bioactive packaging, antimicrobial and antimycotic food coatings, and in the biomedical and pharmaceutical areas.[25] However, one issue at the time of writing is that chitosan still has to gain regulatory approval as a food contact material[3], and thus as chitosan processing and research is expanding, commercial development remains in the production area of the material, mainly for R&D purposes.

Edible films and coatings

Novel properties of bio-based materials are being harnessed to create edible and biodegradable films in a move to prolong shelf life, provide beneficial properties via advanced packaging solutions, and to create a more sustainable industrialised society through reducing packaging waste.[26] However, harnessing these advantageous functionalities is complicated because of a number of limitations such as poor barrier properties (gas and moisture permeability), brittleness and cost.[27 28 29]

Edible films are layers of digestible material used to coat food (edible coatings) or as a barrier between food and other materials or environments (edible films). Food can be coated by dipping into solution, by spraying, or by application with brushes or sponges. Films are created separately and then applied to the food packaging system.[30]

Polysaccharides such as chitosan, starch and cellulose, proteins such a zein and collagen, and lipids such as triglycerides and fatty acids, can be used as edible film-forming materials. The table below shows some of the possible benefits of using bio-based polymers for packaging purposes.

– Edible
– Biodegradable
– Supplement the nutritional value of foods
– Enhanced organoleptic characteristics of food, such as appearance, odor, and flavor
– Reduced packaging volume, weight and waste
– Incorporated antimicrobial agents and antioxidants
– Extended shelf-life and improved quality of usually non-packaged items
– Control over intercomponent migration of moisture, gases, lipids, and solutes
– Individual packaging of small particulate foods, such as nuts and raisins
– Function as carriers for antimicrobial and antioxidant agents
– Microencapsulation and controlled release of active ingredients
– Possible use in multilayer food packaging materials together with non-edible films
– Low cost and abundant
– Annually renewable resources

Table 1: Benefits of and possible uses for bio-based polymers for food packaging (Rhim 2007[31])

[3] In European regulation, No. 1935/2004, EFSA must grant its approval before a substance is authorised for use in food contact materials.

Bionanocomposites created from vegetable and fruit puree and cellulose nanowhiskers have been described in a recent review by de Azeredo[32]. Proteins that can be used include casein, whey, collagen, egg white, and fish derived protein. Soya bean, corn and wheat protein also are candidates for edible films producing proteins.

However, there are considerable differences between the types of biopolymer that can actually be used. For instance polysaccharide films are low cost but exhibit low moisture barrier properties. Protein films have advantageous functional properties such as plasticity, elasticity, and good oxygen barrier properties (similar to polysaccharide) but poor water barrier properties (similar to polysaccharides). Lipid films have good moisture barrier properties but poor oxygen barrier and mechanical properties.

One solution to the deficiencies in these biopolymer films is to create composites. Research and development of bionanocomposites for edible film applications is expected to grow in the next 10 years[33] and the application of bionanocomposites promises to expand the use of edible and biodegradable films in the agrifood sector[34], [35], [36]. A number of works have shown the advantageous properties of incorporating nanoparticles into films, including a recent study from 2009 where chitosan/tripolyphosphate nanoparticles were prepared and incorporated in cellulose films which have shown the improvement of mechanical and barrier properties[37].

Although still a nascent field, there are promising developments that suggest that use of inorganic fillers may improve flavour retention, texture, and colour during transportation process including the reduction of spoilage. [38] There is also the promise of incorporating other substances such as flavour enhancers, antimicrobials and antimycotics.

Nanoparticles can have a dual purpose in this way; providing improvements in the mechanical and barrier properties, but also as carriers of these additives, for example chitosan nanoparticles (mentioned previously) can be modified to exhibit antimicrobial properties. A major application area would be edible antimicrobial coatings for fruit through microencapsulation of antimicrobials. Another branch could be the incorporation of vitamins and other functional ingredients; in this way the edible coating becomes more than a coating, but part of the food.

Technology Readiness Level as an indicator of technology developmental stage

To give a quick reference indication of the status of the nanotechnology research and development, we apply a five step Technology Readiness Level (TRL) system, developed by the ObservatoryNANO partner VDI.

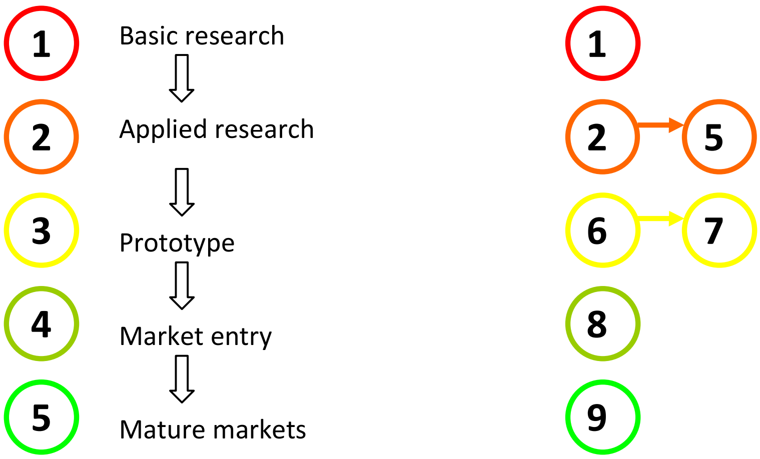

Figure 1: ObservatoryNano TRL scheme corresponding to the US Department of Defence nine point scheme.

Application Area	Technology	Basic Research	Applied Research	Prototype	Market entry	Mature Market
Composite packaging	Polylactic Acid (PLA)/Clay			○		
Composite packaging	Polyhydroxybutyrate/ Clay			○		
Composite packaging	biopolymer and nanowhisker		○			
Composite packaging	biopolymer with nanofibre		○			
Nanomats	Biopolymer Nanofibre mats			○		
Edible films	Biopolymer and cellulose whisker	○				
Edible films	Nanolayers of lipids (such as triglycerides		○			
Edible films	polysaccharide based		○			
Edible films	Protein (e.g. zein, soya, casein)		○			
Edible films	Nanoparticle reinforced		○			

Table 2 –Technology Readiness Level (TRL) assessment of Research and Development status for the technologies described above.

Current situation within the EU

The following FP7 projects funded by the European Commission are relevant to the broad theme of biodegradable and edible films:

- **PLA-FOAM** is focusing on the development of a single-screw extrusion process for production of low density biodegradable PLA foam for thermoformed food packaging applications. This project aims to develop a supercritical CO2 assisted foam extrusion process and thermoforming method that will produce unmodified PLA foam products with greatly reduced thermal degradation. This will enable to produce low density foams using unmodified PLAs whose performance and biodegradation behavior will exceed current alternative.
- Other projects include **NOMATOS** and **HORTIBIOPACK** who are developing innovative and safe biodegradable Equilibrium Modified Atmosphere Packaging film systems based mainly on the use of environmental friendly biodegradable raw materials and aimed at the improvement of the shelf life, quality and safety of specific high value sensitive horticultural fresh produce.
- One part of the research activity **FORBIOPLAST** is seeking forest resource sustainability through bio-based-composite development. This will result in the use of wood and paper mill by-products (bark, chips, sawdust, and black liquor) as raw materials for the production of polyurethane foams by an innovative sustainable synthetic process with reduced energy consumption.
- **BIOSURF** explores amino-functionalised norbornene polymers in order to be further implemented as biocide antimicrobial and anti-deposit surfaces also used in food packaging. All surfaces in contact with food would then be free of potentially hazardous microorganisms.
- The main objective of **BREW-PACK** is to produce multi-layer biopolymer films derived from integrated bio-refining of sustainable biomass which will demonstrate selective gas barrier and functional properties suitable for high performance food packaging.
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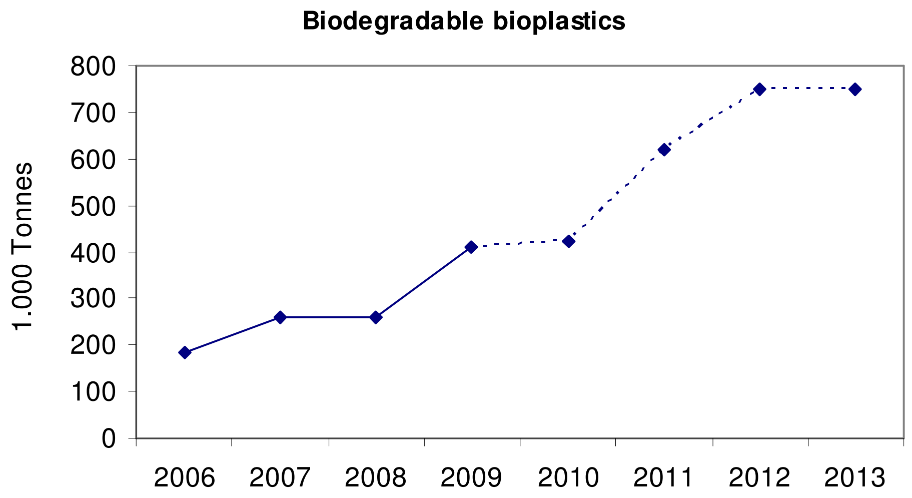
- Development of recyclable long life co-injected high barrier packages employed to preserve foodstuffs from environmental agents, and control the package permeability to gases, is a very important food application being explored within the project **COBAPACK**.
- The main objective of **BADANA** project is to design a process which enables to extract high-quality natural fibre from banana plant waste and to exploit the fibres properties in making polymer composites. These sustainable moulded composite products will be used in the automotive, packaging, and consumer goods industries.
- The idea behind **REBIOFOAM** is to develop a flexible, energy-efficient, and environmentally-sustainable manufacturing process enabling the production of biodegradable foamed 3D-shaped packaging originating from renewable raw materials (such as starch and water).

Economic aspects

General market description

According to Economy Watch, the global food packaging market will reach €5.4 billion by the end of 2010 with a growth rate of 4.3%[4]. The three leading food packaging industries are located in the U.S., Europe and Asia. Regarding biodegradable packaging the market has been developing rapidly over the last decade and, although exact figures of this development are not accessible, a number of estimations denote an annual growth greater than 20 %.[5] According to the European Bioplastics association, the global production of biodegradable bioplastics reached an annual capacity of 400 thousand tonnes in 2009.



Source: European Bioplastics association (http://www.european-bioplastics.org)

In addition to this relatively high growth, the current market is also characterized by increasing diversification. This is evident firstly in the growing number of materials, applications and products, and secondly in the increasing fragmentation of the market at all stages of the value chain resulting in a growing number of companies developing biodegradable packaging.

Also the number of nano-based packaging applications is also reported to be on the rise. Three years ago fewer than 40 packaging products containing nanoparticles were thought to be on the market, compared to the 400 plus reported today. Currently, nanoclay particles are the most common commercial application of nanoparticles in food packaging and account for nearly 70% of the market volume (the market for food packaging containing nanomaterials has been predicted to reach $20bn by 2020)[6].

Many companies in the market for bio-based packaging are undergoing rapid expansion to keep up with growing demand. For example, bioplastics developer Cereplast reported a 134% increase in gross sales for the first quarter in 2009. Companies like DuPont Packaging and

[4] http://www.economywatch.com/world-industries/packaging/food.html

[5] http://www.basf.com/group/pressrelease/P-08-229 or http://www.reportlinker.com/p091955/US-Biodegradable-Plastics-Market.html

[6] See http://www.packaging-gateway.com

Industrial Polymers and Arkema Inc. have also entered the market with modifiers that alter or improve the properties of biopolymers. Overall, green packaging is fast becoming a primary focus of the food and beverage packaging industry.

Economic drivers

There are at least three main economic drivers for higher production and broader use of biodegradable packaging.

Long-term availability and price of fossil resources

Currently plastic based packaging covers a significant part of packaging industry. The global consumption of plastics (in total, not only packaging) amounts to more than 250 million tonnes per year representing the largest field of application for crude oil outside the energy and transport sectors.[7] This indicates the high dependence of the packaging industry on oil prices (including dependence on availability of fossil fuels in the medium and long term). The recent dramatic increase in oil prices has made non-fossil fuel derived plastics increasingly more attractive.

Waste management

The rapid growth in plastic packaging has generated many concerns about the ecological impact of food packaging, which in turn has led to a rise in demand for eco-friendly packaging materials. Biodegradable packaging has the potential to be composted, without the need for preceding separation. The role of nanotechnologies here could significantly reduce costs and energy of waste management, since they enable producing lighter and less capacious packaging.[8]

Consumer demand

The influence of consumer demand on nanotechnology use in biodegradable packaging is somewhat ambiguous. As for the biodegradable packaging, consumers are very keen on seeing more products using biodegradable plastic packaging on the market. This was revealed from the results of a large survey on consumer reaction to biodegradable packaging carried out by a consortium of more than 30 parties from different sectors (science, public administration, business, etc.)[9]. Almost 90% of respondents support the idea of replacing conventional plastic packaging by biodegradable plastic packaging and more than 30% of consumers would be prepared to pay a higher price for biodegradable packaging. On the other hand the public attitude towards the use of nanotechnologies in food or food contact materials is distinguished by high degree of uncertainty, scepticism, wariness, or even refusal. This was highlighted by the FSA Evidence Review of Public Attitudes to Emerging Food Technologies published recently.[10] This report also indicates that attitudes to novel food technologies in the USA and Asia seem to be generally more positive than in Europe. Nevertheless, we can suppose that the general public attitude to nanotechnologies in food packaging might be less negative than to nanotechnologies incorporated into food itself. This was to a certain extent proved by the PEN survey, where 12 % would buy nano-based packaging (although 73 % would require more information about

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[7] See European Bioplastics association (http://www.european-bioplastics.org).
[8] See also the statement of the Royal Society of Chemistry in House of Lords: Nanotechnologies and Food, Volume II, 2009, p. 236 (http://www.publications.parliament.uk/pa/ld/ldsctech.htm) .
[9] For more information see http://www.modellprojekt-kassel.de/
[10] See Lyndhurst, B.: An Evidence Review of Public Attitudes to Emerging Food Technologies. Food Standards Agency, March 2009.

potential risks), whereas only 7 % of respondents would buy food containing nanotechnologies (62 % would require further information).[11]

Regulation and legislation

Since biodegradable packaging is still in its initial stage of market development, regulation and standardisation play an important role for the future direction. At the European level all biodegradable packages (packaging films) have to fulfil the European composting norm EN 13432:2000, and in the US they must be certified to the American standard ASTM6400.

Regarding nanotechnologies in food packaging, their use in Europe is in principle sufficiently[12] regulated by the Regulation EC/1935/2004[13] that covers all materials come into contact with foodstuffs. According to this regulation the EC or individual Member States may ask the European Food Safety Authority (EFSA) to conduct a safety evaluation of food contact materials. Food contact plastics are subject to additional measures regulated by the Regulation (EC) 282/2008 on recycled plastic materials and articles[14] and by the Regulation (EC) No 450/2009 which sets down additional requirements to Regulation (EC) No 1935/2004 for active and intelligent materials and articles.[15]

Although there are no stimulatory measures towards broader use of biodegradable packaging at the European level, at the national level Germany has already introduced legislation that favours certified biodegradable plastics packaging against conventional plastics packaging.[16]

Economic barriers

Cost

In contrast to the production of conventional plastics, bioplastics are produced in a smaller volume, which does not allow benefiting from economies of scale. Therefore the cost of bioplastics production still remains above the crude oil based plastics. However, due to the expected increase in crude prices and continuous growth of bioplastics market this gap is predicted to gradually diminish.

Another economic barrier could be the low consumer demand caused by a negative attitude of consumers to novel technologies in food (see above).

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[11] See PEN: Poll Reveals Public Awareness of Nanotech Stuck at Low Level, News Release, September 2007 (http://www.nanotechproject.org/process/assets/files/5970/092507nanotechnology_pollresults09_07.pdf)

[12] The FSA regulatory review "A review of potential implications of nanotechnologies for regulations and risk assessment in relation to food" published in August 2008 has not identified any major gaps in regulations relating to the use of nanotechnologies in food.

[13] See http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2004:338:0004:0017:EN:PDF

[14] See http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2008:086:0009:0018:EN:PDF

[15] See http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2009:135:0003:0011:EN:PDF

[16] For more information see the Ordinance on the Avoidance and Recovery of Packaging Wastes (http://www.bmu.de/files/english/waste_management/downloads/application/pdf/verpackv_3aenderung_en.pdf)

Selected company profiles

Key market players on the food packaging market (non nano specific)

Tetra Pak has a 80% share of the carton packaging market, and exercises considerable influence over its paperboard suppliers. It provides a wide range of aseptic packaging for chilled beverages and high acid drinks. China is currently Tetra Pak's largest growth market producing 27 billion packages. Tetra Pak has shown an increase in focus on sustainability, through sourcing material from sustainable forests, and on recyclability of its packages. Tetra Pak spends around 3.5 % of its annual sales revenue on research and development, and has patented a method of manufacturing plastic gas barrier packaging laminate.

As the world's largest PET container supplier **Amcor** provides a number of products including plastic containers for beverages, partially demetallised flexible packaging, and protection for pharmaceuticals with varying moisture level of barrier protection. Advanced technology is used for producing film packaging with controlled permeability preventing dehydration, which could create the ideal atmosphere for every product and delay its ageing process. Amcor Australasia and Plantic Technologies Limited are collaborating on a research programme towards the development of a new biodegradable material for the commercial packaging market. Plantic will provide its patented plastic material created from plants which has been described as one of the most significant advancements in packaging technology in the last decade, and Amcor will use the Plantic® material to expand it into flexible packaging and further advance the technology.

Sirap Packaging, having a turnover of approximately €264 million in 2008, holds the top position among the biggest producers of rigid and foam plastics for food packaging as to give food longer shelf-life. European market leader in food packaging operates twelve factories built according to the market demands and other sub-divisions operating in France, Spain, Poland and Russia.

DuPont Liquid Packaging Systems is a leading global supplier of flexible packaging to the liquid food and beverages. The invention of polyethylene films comes from DuPont research developed over 40 years ago. They combine novel materials with advanced equipment to provide comprehensive range of aseptic or extended shelf life packaging and access to safe and nutritious food and beverages on worldwide basis.

Company Name	Tetra Pak	Amcor	Sirap Group	Du Pont Packaging & Industrial Polymers
URL	HTTP://WWW.TETRAPAK.COM/PAGES/DEFAULT.ASPX	HTTP://WWW.AMCOR.COM/	HTTP://WWW.SIRAPGEMA.COM/	HTTP://WWW.DUPONT.COM/
Revenue	€8.825 billion (2008)	AU$ 9.960 million (2009)	€1.358 million (2006)	$51.9 million (2009)
Number of employees	21.640 (2009)	21.000 (2009)	1.500 (2009)	5.500 employees (2009)
Public funding received (Y/N)	N/A	YES	N/A	N/A
If Y: Amount, Year	N/A	$256 million, 2008	N/A	N/A
Description	Food packaging	Packaging	Packaging and Containers	Packaging, Plastics

Selected innovation companies involved in production of biodegradable packaging

EcoSynthetix Inc. is a Canadian company founded in 1996 in order to develop and commercialise high-tech bio based materials with performance capabilities at least equal to the traditional petroleum-based products. EcoSynthetix has an IP portfolio comprising of 18 patents and patent applications for new technologies for manufacturing environmentally friendly biopolymers (for example US Patent No. 6921430: Environmentally friendly biopolymer adhesives and applications based thereon). In the beginning of 2010 the company has closed a USD $10.1 million Class A-3B preferred share financing (managed by the fund of venture capital funds VentureLink LP). The new funding will be used for expanding production, sales and marketing efforts this year. According to the managing partner of VentureLink LP Jim Whitaker, "EcoSynthetix has the opportunity to replace a sizeable portion of the four billion pounds of petroleum based latex used in the production of coated paper and paperboard."[17]

Novamont, an Italian company founded in 1989 is described as a pioneer in the bioplastics sector. Since its foundation, Novamont has invested over € 82 million in research and development including active collaboration with institutions and integration with its partners. The turnover of Novamont exceeds € 40 million, whereas approximately 12% of turnover is

[17] See http://www.tradingmarkets.com/news/stock-alert/ccorf_ecosynthetix-closes-10-1-million-financing-696602.html

reinvested in research. The number of employees runs to 120, around 30% work in R&D, Novamont has been involved in the production of films, packaging, additives for tyres, canvases for mulch, and products for the home produced using entirely biodegradable materials. The business success of the company is based on the product Mater-Bi (see below). The company has received a prestigious international award in the UN environmental programme in 2002 for its commitment to environmentally sustainable products.

TopChim is a chemical company based in Belgium and Brazil, specializing in paper and cardboard coating technology, founded in 1996. The company is operating especially in Europe and the Far East. In 2008, TopChim has signed an agreement with the Institute for the promotion of Innovation by Science and Technology in Flanders (IWT) and the Centre for Materials Science and Engineering (CMSE) of Ghent University to start a new R&D projects on polymer nanoparticles. This project has a total budget of €900 thousand. In October 2009 it concluded a strategic partnership with the US Company Cargill Inc. to produce a sustainable line of products in Brazil to be used for paper and board applications. In June 2009 TopChim has started new development initiatives to initiate product innovation with organic nano-materials for other industrial applications.

Plantic Technologies Ltd is an Australian company established in 2001 for the purpose of commercialising intellectual property developed by the Cooperative Research Centre for International Food Manufacture and Packaging Science (an Australian Federal Government funded research group). In 2004, Plantic Technologies began operations in Europe, with its sales offices in Germany and the United Kingdom; however, head office, principal manufacturing and R&D facility remain in Australia. They have a turnover of $ 3.5 million and employ 50 people internationally. Plantic Technologies' business is based on patented technology that delivers a completely biodegradable and organic alternative to conventional plastics based on corn, which has not been genetically modified corn. In 2010 Plantic Technologies announced a new distribution agreement in the US for the biopolymer rigid packaging films. The company has an exclusive partnership with the Klöckner Pentaplast Group (a global producer of rigid packaging films). Klöckner will sell Plantic rigid packaging films throughout the US under its Pentafood Biofilm brand name.

Rohm and Haas is a company established in 1909 with headquarters located in the US. Since 2009 the Rohm and Haas is a wholly owned subsidiary of The Dow Chemical Company (the Dow Chemical Company both Rohm and Haas for $17.3 billion). The company is characterized by more than 100 manufacturing, technical research, and customer service sites in 27 countries, more than 16,500 employees in scientific, business, marketing, and service disciplines. The annual sales revenue ran to approximately to $8.2 billion in 2006. The company specializes in producing advanced materials applicable in various industries. With regard to the food packaging industry Rohm and Haas is mainly focusing on bioplastic materials, specifically on PLA.

Selected Products

In general, attitudes in the USA appear to be more positive than in Europe across most of the technologies. Americans are not the only ones who have more positive attitude to science and technology and higher levels of trust in their regulatory authorities; consumers in Asia also tend to be more optimistic about novel food technologies. However, in the EU public acceptance can vary substantially. According to the Food Standards Agency (FSA) it is not possible to provide a definitive list of nanofoods and nanoscale food contact materials on the EU market, primarily because of the absence of an EU-wide register or inventory. Underlying this practical difficulty is the more fundamental issue of the absence of a common definition of nanotechnologies and nanomaterials. Very few entities are able to offer, unreservedly, a description of the usage of nanotechnologies in food sector. Nonetheless, there is some evidence of the current use of nanotechnologies for food packaging in form of specific products.

EcoSphere® Biolatex™: nanoparticle starch-based latex

Cardboard manufacturers currently use roughly four billion pounds of starchy adhesive a year across 1,700 plants worldwide to glue together the paper layers that make up corrugated containers. **EcoSynthetix Inc.** specializes in the manufacturing and commercialization of biobased products and technologies derived from renewable resources that have a positive impact on the environment. The company's biopolymer nanoparticle technology platform provides EcoSphere biolatex products as replacements for petroleum-based paper and paperboard coating binders such as SB and SA Latex. At substitution levels up to 50 %, the biolatex products are comparable, or superior to, traditional petroleum-based alternatives and can be specifically formulated to deliver previously unattainable benefits at a lower delivered cost to industrial users.

Ecosynthetix is now converting two plants to run on their adhesives. Its technology is based on converting natural starch particles (particle-size 30μm) into nanoparticles (particle-size 50-150 nm). The nanoparticles possess 400 times greater surface area than natural starch granules requiring less water in use for adhesives, less time and energy for drying, and thus saving $1 million in natural gas per year. The nanoparticle adhesives could also help replace the polyvinyl acetate (PVA) and polyvinyl alcohol (PVOH) used to help laminate graphics onto cardboard. The market for PVA and PVOH in lamination was $1.3 billion in 2005. The nanoparticles could also find use as the first biosynthetic waterborne starch latex, to replace up to 75 % of the petroleum-based latex known as SBR, used currently as a binder in paper coatings, which constituted a $2 billion market in 2005.

EcoSphere biolatex is unique because its discrete particles are insoluble and thus form an aqueous polymer colloid. The production process converts starch into a thermoplastic melt that is transformed into an agglomerate of dry cross linked biopolymer nanoparticles. Dry product is shipped directly to the customer, where it is readily dispersed in water to form the EcoSphere biolatex dispersion. This therefore eliminates the cost of shipping water. EcoSphere biolatex emulsions provide a variety of benefits to the coated paper and paperboard manufacturer.

Mater-Bi® Nanostarch

Mater-Bi® Nanostarch is a brand name of product presented by the **Novamont** at the K2007 trade fair. The Nanostarch is bioplastics based on vegetable starches which enable mimicking behaviour of traditional plastics. The Nanostarch represents yet another important technological step forward towards bringing second generation bioplastics to the market. Through its patented technology the starch is transformed into the component to be used for improved bioplastics performance. Mater-Bi® Nanostarch is fundamental for production of ultra-thin and super-strong products even in low-humidity conditions. Amongst those who can benefit from this breakthrough technology are all flexible film sectors requiring high strength from thin films even in critical operating conditions.

Novamont is increasing its manufacturing capacity by expanding its biorefinery in response to the growth in market demand for bioplastics. The plant is completely integrated into its local environment and will use local natural resources of agricultural origin. The biorefinery has started working at its full capacity in 2008, and will reach an annual production capacity of 60 000 tons of completely biodegradable bioplastics with minimal environmental impact throughout their life cycle. Bioplastics can be recovered and recycled by methods of thermal recovery, organic recycling (composting), and chemical recycling. The Novamont bioplastics have been developed according to the guidelines, in which composting is considered to be the most cost-effective method of disposal.

TopScreen DS13: nano-dispersed biopolymer

The packaging industry is seeking easy recyclable and environmental friendly packaging solutions sourced from renewable resources. ***TopChim***, an established research-driven chemical company applies the latest technologies in chemical science to develop high-performance ecological coating solutions for the paper and cardboard industry. Its new technology is the result of active collaboration with European institutes and universities involved in fundamental research in chemistry. TopChim released ***TopScreen DS13*** in 2008, an environmental friendly, patented, nano-dispersed biopolymer to substitute wax emulsions in super hydrophobic paper and cardboard packaging.

TopScreen DS13 is water based coating which contains a biopolymer with a monodisperse distribution of nano-particles with a regular shape. It is developed to replace hard-to-recycle wax emulsion coatings used as water barriers in paper and board packaging. Paper and cardboard coated with TopScreen DS13 requires no stabilizers and is as easily repulpable as non-treated paper or cardboard. Furthermore, TopScreen DS13 is thermally resistant and less sticky than wax. This biopolymer can be used for packaging with food contact and has no negative impact on the recyclability or biodegradability of the packaging. TopChim has a total production capacity of 10.000 tons at 2 plants in Europe and plans to invest in additional production of this biopolymer in South America.

Nanocomposite starch/clay

Plantic Technologies Ltd is engaged in the development and commercialisation of various environmentally friendly plastics made from renewable resources across a broad range of applications with a particular focus on the packaging industry. One part of Plantic's global patent portfolio relates to provisional patent disclosed in 2007 on new nano-composite materials, which include starch and substantially exfoliated hydrophobic clay. This recent invention is the result of research and development efforts in partnerships with research centres (CRC), organisations, several universities and Commonwealth Scientific and Industrial Research Organisation (CSIRO). CSIRO introduced clear plastic bottles coated with a nanocomposite that protects against heat, UV light or other wavelengths to prevent 'light strike' affecting the flavour of the liquids inside the packages. Plantic intends to intensify using nano-composites in its products since this material improves impact toughness, enhances gas barrier performance, and offers a high degree of transparency. These benefits have the potential to broaden significantly the range of packaging and other applications in which Plantic's biodegradable products attempt to be incorporated.

PARALOID™ BPM-500: nanoscale additive for PLA

PARALOID™ BPM-500 is a product of **Rohm and Haas**, the company with a tradition in bringing the environmentally friendly products on packaging market. In time when packaging is largest end market for polylactic acid (PLA) with over 50% of the consumption, Rohm and Haas is mainly focusing on bioplastic materials, specifically on PLA. BPM-500 as an acrylic impact modifier has been especially designed to improve the impact resistance of PLA resin for industrial use and more specifically for transparent packaging applications. The unique balance of impact performance and clarity is achieved through a nanoparticle size distribution, good dispersion and refractive index match between the nanoscale particles and the PLA matrix. In addition to better impact properties, PLA modified with BPM-500 shows a marked improvement in cutting of PLA extruded sheets and slitting, in addition to increased flexibility. Paraloid modifiers enable bioplastics to compete with traditional thermoplastics in packaging applications. The addition of BPM-500 also increases the resistance of the film to tearing and improves cutting.

SonoCoat PAN: equipment for application of nano coatings

Sono-Tek presented Ultrasonic Atomization Technology at Nanotechnology the 6th annual National Nano Engineering Conference (NNEC). This technology provides efficient solutions for accurately and cost effectively dispersing and depositing edible antibacterial nanomaterials on target substrates. Nanocoating could provide a barrier to moisture and gas exchange, act as a vehicle to deliver colours, flavours, antioxidants, enzymes and anti-browning agents, and may also increase the shelf life of foods, even after the packaging is opened.

In 2009, Sono-Tek also announced the sale of a new industrial depanning oil coating system, the SonoCoat PAN. The equipment was developed for a global baked goods conglomerate which owns and operates numerous baking plants. The system has the potential to become the standard operational unit at the customer's baking lines worldwide, replacing current conventional spraying system technologies. This system offer better transfer efficiency with less bounce back of liquid from the target and a more controllable, uniform coating application of nano to micron thickness levels. Within the bakery sphere, SonoTec’s spray coating systems are not just suitable for depanning. The company recently sold an edible oil spray coating system to Mesa Foods and it is now working on additional applications, including spray coating of antimicrobial solutions and moisture barriers for safety and shelf life extension.

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