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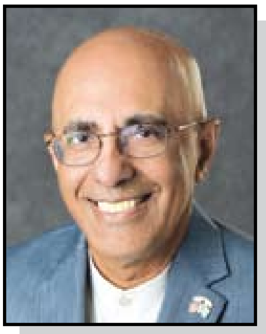
THE PROMISE OF NEW BIOBASED AND COMPOSTABLE POLYMER MATERIALS IN HARMONY WITH EMERGING "CIRCULAR ECONOMY" CONCEPTS – SYNERGY & OPPORTUNITY FOR PAPER INDUSTRY



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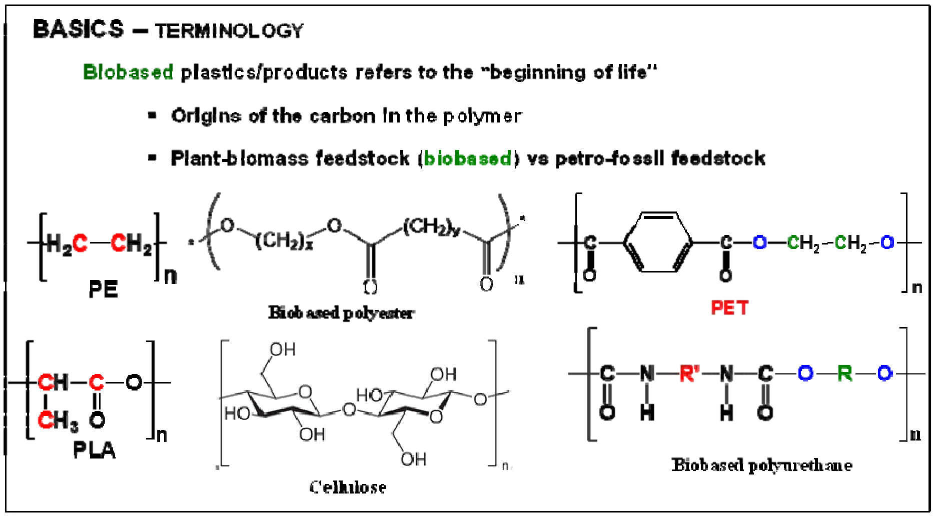
This lecture-workshop introduces the exciting new world of emerging biobased and compostable/recyclable polymer materials. The lecture will present the value proposition for these new biobased polymer materials, the science behind the design for environmentally responsible end-of-life for these products, the fit with the global theme of "Circular Economy". Paper and paper products are also manufactured from the same biomass feedstocks and provides a compelling synergy with these new biomaterials as well as new business opportunities.

Polylactide under the tradename Ingeo[tm] is the world's foremost 100% biobased and compostable as well as recyclableresin material manufactured byNatureWorks LLC -- the PLA story from laboratory curiosity to current commercial operations of 150,000 tons will be briefly reviewed. The NatureWorks team (www.natureworksllc.com) will be in attendance to share their story and success.

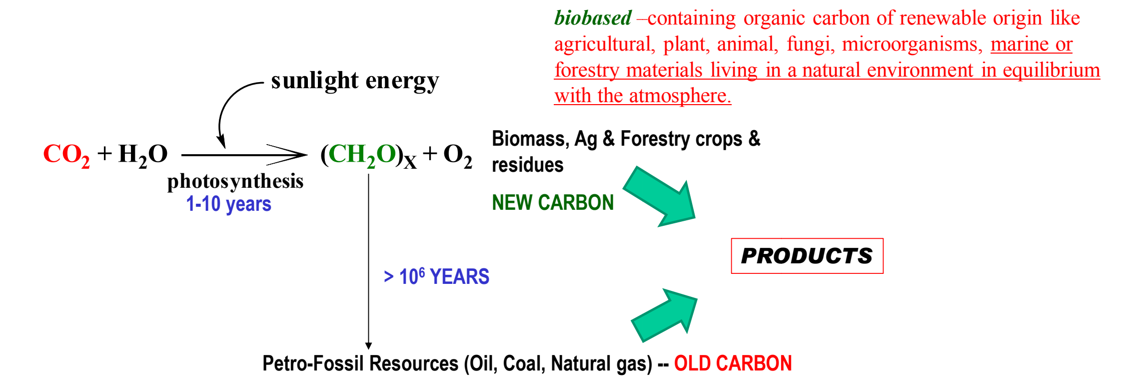


Biobased Polymer Materials &Value Proposition

Biobased plastics and products contain organic carbon of renewable origin like (from) agricultural, plant, animal, fungi, microorganisms, marine or forestry materials living in a natural environment in equilibrium with the atmosphere – ASTM D6866 – see attached figure.

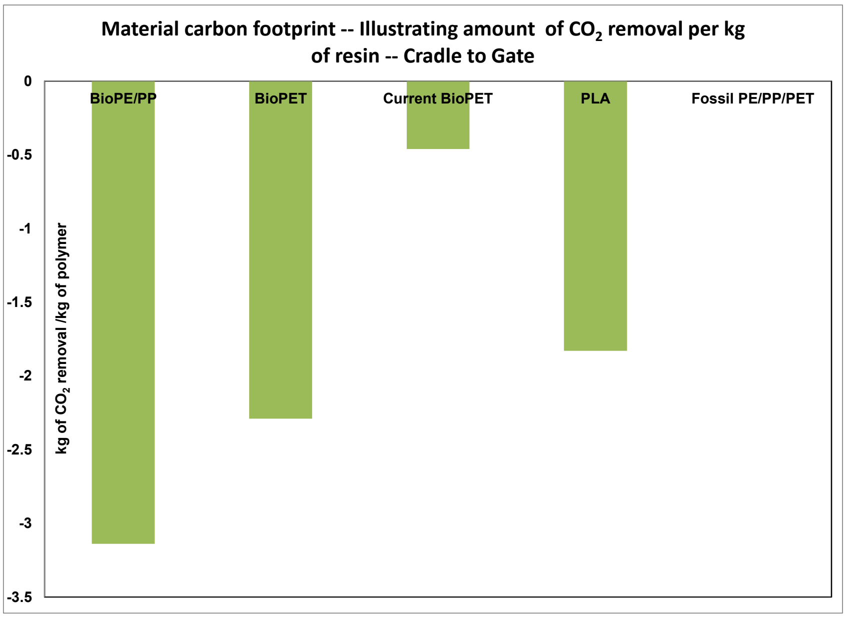
Replacing petro/fossil carbon with biobased carbon (from plant-biomass feedstocks) in plastics and industrial products offers the value proposition of removing carbon present as CO_2 in the environment and incorporating it into a polymer molecule via plant-biomass photosynthesis in a short time scale of one (agricultural crops, algae) to 10 years (short rotation wood and tree plantations) in harmony with Nature's biological carbon cycle. Products made from petro/fossil resources (like Oil, Coal, Natural gas) which are formed from plant biomass over millions of years and so cannot be credited with any CO_2 removal from the environment even over a hundred-year time scale (the time period used in measuring global warming potential, GWP100). Process carbon and environmental footprint (arising from the process of converting the feedstock to product) are also improved. This concept is shown in the attached figure.

years



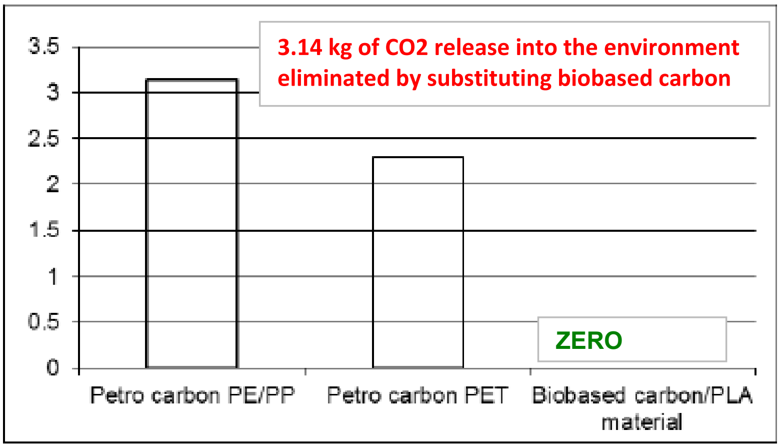
- Using plant-biomass carbon feedstocks removes CO_2 from the environment and incorporates it into a polymer molecule via plant-biomass photosynthesis in a short time scale of one (agricultural crops, algae) to 10 years (short rotation wood and tree plantations) in harmony with Nature's biological carbon cycle
- Petro/fossil resources which are formed from plant biomass over millions of years and so cannot be credited with any CO_2 removal from the environment even over a 100 year time scale (the time period used in measuring global warming potential, GWP100)

The biobased carbon content of products is determined independently and unequivocally using radio carbon analysis as codified in International Standards – the primary one is the ASTM D6866 (Standard Test Method for determining biobased (carbon) content of solids, liquids, and gaseous samples using radiocarbon analysis). Using experimentally determined biobased carbon content and applying fundamental stoichiometric calculations, one can readily calculate the amount of CO_2 removed from the environment by1 kg of material. For example: 1 kg of biobased polyethylene (PE) containing 100% biobased carbon content would result in removing 3.14 kg of CO_2 from the environment. 1 kg of PLA (100% biobased carbon content) would remove 1.83 kg of CO_2 from the environment. 1 kg of the current bio PET (20% biobased carbon content – only the glycol carbons come from plant-biomass) results in 0.46 kg of CO_2 removal from the environment. 1 kg of the 100% biobased carbon content PET results in 2.29 kg of CO_2 removal. In contrast, the petro-fossil carbon based products results in zero CO_2 removal from the environment. These results are graphically shown in the figure below.



Eventually, at the end-of-life of these plastics, the carbon will be released back into the environment as CO_2 through waste-to-energy systems or incineration or through composting or anaerobic digestion (if it has biodegradability-compostability feature built into it. However, the CO_2 released will be captured by the next season's crop or biomass plantation resulting in a net zero material carbon footprint, in harmony with Nature's carbon cycle. In contrast, the non-biobased PE or PP will contribute a net 3.14 kg of CO_2 into the environment for every 1 kg of PE used. 1 kg of PET will contribute 2.29 kg of CO_2 to the environment.

In summary, the replacement of petro-fossil carbon in whole or part by biobased



carbon (derived from plant biomass resources) offers the value proposition of reduced carbon footprint and the enabling technology to move towards the closed loop "circular economy" model that is being advocated and adopted by many nations and major industrial organizations and brand owners.

Biodegradability-Compostability – End-of-Life scenario

The biobased carbon value proposition for plastics articulated above does not address its end-of-life – the question of what happens to product after use when it enters the disposal environment. Biobased plastics are not necessarily biodegradable-compostable and all biodegradable-compostable plastics are not automatically biobased. The biobased carbon content has zero impact on the end-of-life of the biodegradable plastics. The molecular structure of the plastic and the availability of its carbon for transport into the microbial cell and subsequent utilization for energy drives the microbial assimilation (percent biodegradability) of carbon substrates like plastics -- the availability of carbon in a molecule to the microbes and not the source of the carbon is the key learning.

Science of Biodegradability

Biodegradability is an end-of-life option that allows one to harness the power of microorganism present in the selected disposal environment to completely remove plastic products designed for biodegradability from the environmental compartment via the microbial food chain in a timely, safe, and efficacious manner. Terms like "oxo", "hydro", "chemo", "photo" degradable describe abiotic (non-biological process) mechanisms of degradation. They do not constitute or represent "biodegradability" -- the biological process by which microorganisms present in the disposal environment assimilate/utilize carbon substrates as food for their life processes -- see attached figure.

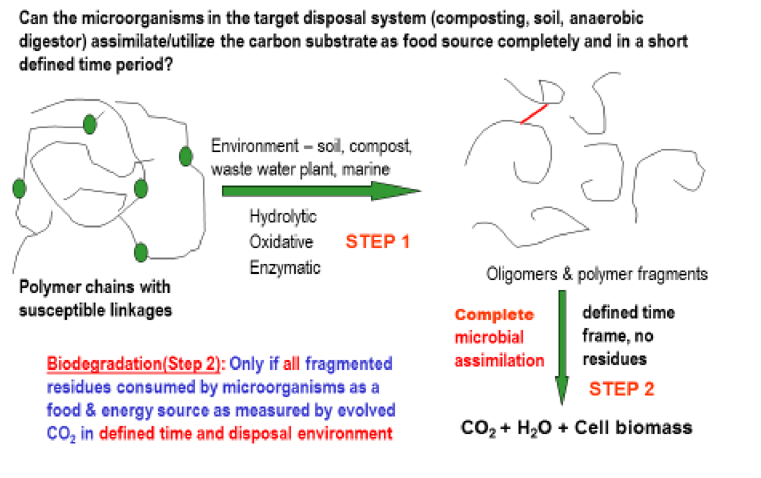


Figure -- Understanding biodegradability

Because it is an end-of-life option, and harnesses microorganisms present in the selected disposal environment, one must clearly identify the "disposal environment" when discussing or reporting the biodegradability of a product – for example, biodegradability in composting environment (compostable plastic), biodegradability in soil environment, biodegradability under anaerobic conditions (in anaerobic digestor environment or even a landfill environment), or biodegradability in marine environment.

Reporting time to complete biodegradation or more specifically the time required for the complete microbial assimilation of the plastic in the selected disposal environment is an important requirement. Product claims stating that plastic will eventually biodegrade based on data showing an initial 10-20% biodegradability is not acceptable and very misleading especially since the percent biodegradation levels off and reaches a plateau after some initial rate and level of biodegradation. Drawing a straight line extrapolation from the initial rate and value to 100% biodegradation is scientifically untenable, and unfortunately many of the claims are based on this type of extrapolation

Measuring and reporting on biodegradability

Basic biology teaches how microorganisms utilize carbon substrates as food for their life processes. Carbon substrates including any biodegradable plastics have to be transported into the microbial cell. The transport is governed by several factors like molecular weight, structure, functional groups, hydrophilic-hydrophobic balance, and other special factors. Inside the cell, the carbon is biologically oxidized to CO_2 releasing energy that is harnessed by the microorganisms for its life processes. Under anaerobic conditions, CO_2+CH_4 (biogas) are produced (see Figure). Thus, a measure of the rate and amount of CO2 or CO_2+CH_4 evolved as a function of total carbon input to the process is a direct measure of the amount of carbon substrate being utilized by the microorganism (percent biodegradation).

Aerobic process

$$\text{Glucose/C-bioplastic} + 6O_2 \longrightarrow 6CO_2\uparrow + 6H_2O;\ \Delta G^{0\prime} = -686\ \text{kcal/mol}$$

Anaerobic process

$$\text{Glucose/C-bioplastic} \longrightarrow 2\ \text{lactate} \longrightarrow 3CO_2\uparrow + 3CH_4\uparrow\ \ \Delta G^{0\prime} = -47\ \text{kcal/mol}$$

Figure Basics for the microbial utilization of carbon substrates

It would seem obvious and logical from the above basic biology lesson that to make a **claim of biodegradability**, all that one needs to do is the following: Expose the test plastic substrate as the sole carbon source to microorganisms present in the target disposal environment (like composting, or soil or anaerobic digestion or marine), and measure the CO_2 (aerobic) or CO_2+CH_4 (anaerobic) evolved. A measure of the evolved gas provides a direct measure of the plastics carbon being utilized by the microorganisms present in the target disposal environment (% biodegradation). ASTM, EN, and ISO test methods teach how to measure the percent biodegradability in different disposal environments based on the fundamental biochemistry described above -- irrespective of what the initial degradation is – oxo, hydro, chemo, the abiotic degradation.

Thus, one can measure the rate and extent of biodegradation or microbial utilization of the test plastic material by using it as the sole carbon source in a test system containing a microbial rich matrix like compost in the presence of air and under optimal temperature conditions (preferably at 58^0 C – representing the thermophilic phase). The attached figure shows a typical graphical output that would be obtained if one were to plot the percent carbon converted to CO_2 as a function of time in days. First, a lag phase during which the microbial population adapts to the available test C-substrate. Then, the biodegradation phase during which the adapted microbial population begins to utilize the carbon substrate for its cellular life processes, as measured by the conversion of the carbon in the test material to CO_2. Finally, the output reaches a plateau when all of the substrate is completely utilized. Linear or any other form of data extrapolation from these complex biological systems is not acceptable and is very misleading because credible scientific substantiation for the extrapolation model does not exist.

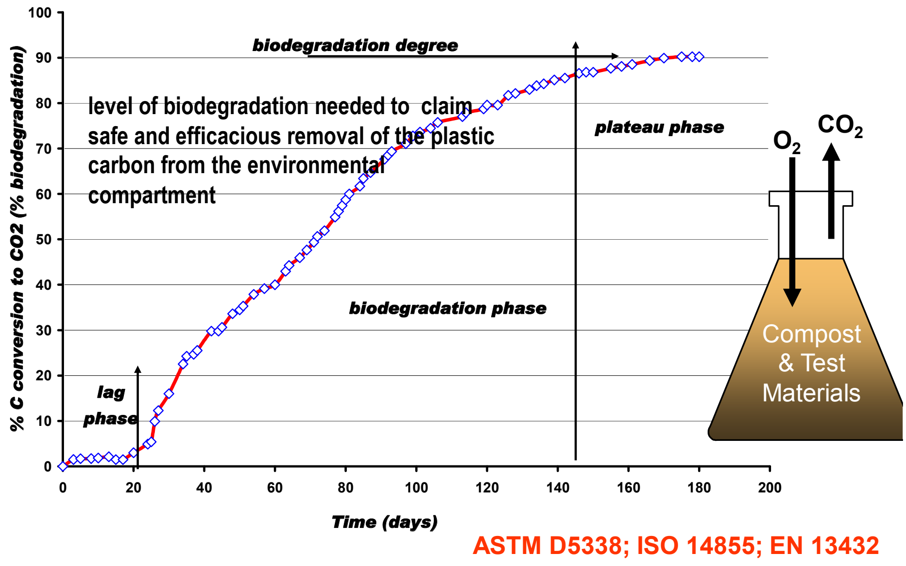


Figure 3. Measuring rate and extent of biodegradability using test plastic as the sole carbon source

Claims of degradable, partial or extrapolated biodegradability or eventual biodegradable are not acceptable, because it has been shown that these degraded fragments absorb toxins present in the environment, concentrating them and transporting them up the food chain. Therefore, complete removal from the disposal environment is a short time period of 1-2 years is essential to eliminate potentially serious human health and environmental consequences

International Standards for Biodegradability

To meet the requirements of biodegradability under industrial composting conditions (compostable plastics), a plastic must satisfy the primary requirement of complete biodegradability as measured by the microbial conversion of the plastic carbon to CO_2 under composting conditions, as discussed in the earlier section. In addition, it has to meet the disintegration and safety criteria to make a claim of compostability. ASTM D6400, D6868, ISO 17055, and EN 13432 are specification standards for compostable plastics. Another ISO specification standard ISO 18606 addresses "Packaging and the environment – Organic recycling" and follows the same basic principle outlined above.

Specification Standards set the pass/fail criteria and is based on a standard test method. Standard test methods teach practitioners how to conduct biodegradability tests in the selected environment, how to collect data from the test, and how to correctly report the results of the tests. There are no pass/fail criteria. Unfortunately, many companies make unqualified claim of biodegradability and label their plastic product "biodegradable" referencing a standard test methods without providing actual percent biodegradability values obtained in the test – a graphical display of the percent biodegradability (measured by the evolved CO_2 or CO_2+CH_4) as a function of time in days. This is misleading as the consumer or stakeholder assumes that the product is completely biodegradable. Tables 1 and 2 at the end of this document provide a list of international specification standards and test methods.

Misleading Claims of Biodegradability

There are additive based plastics – oxo-degradable and organic additives added at 1-2% levels to conventional hydrocarbon resins like polyethylenes (PE), polypropylene (PP), polystyrene (PS), polyethylene terephthalate (PET) and other plastics that are claimed to make them 'biodegradable'. However, the fundamental biological data showing percent carbon utilized or assimilated by the microorganisms, as measured by the evolved CO2 (aerobic) or CO2 +CH4 (anaerobic), are not provided. Some of the data show 10-20% biodegradation which then levels off with little or no biodegradation. Weight loss, molecular weight reductions, carbonyl index, mechanical property loss, biofilm formation, and microbial colonization do not confirm the microbial utilization of the polymeric carbon substrate, nor do they provide the amount of carbon utilized or the time to complete microbial utilization.

U.S. Federal Trade Commission (FTC) Green Guides

The U.S. Federal Trade Commission (FTC) recently issued new Green Guides, on Environmental Marketing Claims to help marketers avoid deceptive environmental claims. The FTC guides state that an "unqualified degradable claim for items entering the solid waste stream should be substantiated with competent and reliable scientific evidence that the entire item will **fully decompose** (break down and return to nature; i.e. decompose into elements found in nature) **within one year** after customary disposal". It also emphasizes that unqualified degradable/ biodegradable claims for items that are customarily disposed in landfills, incinerators, and recycling facilities are deceptive because these locations do not present conditions in which complete decomposition will occur within one year.

The term fully decompose into elements found in nature equates to the complete abiotic and biotic breakdown of the plastic to CO2, water, and cell biomass via microbial metabolism. This is discussed in detail in the earlier sections.

Degradable claims can be made if it is qualified clearly and prominently to the extent necessary to avoid deception about:

• The product's or package's ability to degrade in the environment where it is customarily disposed and more importantly **the rate and extent of degradation/biodegradation.**

In the case of biodegradability claims, one has to provide "reliable and competent science based evidence" of the rate and extent of biodegradation in the target disposal environment – a graphical plot of percent biodegradability as measured by the evolved CO_2 (aerobic) or CO_2+CH_4 (anaerobic) vs time in days. The FTC guides do not identify any specific testing protocol or specification and therefore reserve the right to evaluate the data which forms the basis of the claims. However, they clearly require that the evidence should be based on standards generally accepted in the relevant scientific fields. So ASTM, EN, ISO standards should be used to provide the evidence for validating the rate and extent of biodegradation in the selected disposal environment/s

In summary, claims of a plastic product's biodegradability must be qualified by graphically showing the percent product carbon being utilized (percent biodegradation) by microorganisms present in the selected disposal environment as measured by the evolved CO_2 (aerobic) or CO_2 +CH_4 (anaerobic) as a function of time in days in the selected disposal environment.

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