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BIO-BASED PLASTICS:

NAVIGATING THE TRADE-OFFS

To move bio-plastics forward, several lifecycle issues surrounding these new products must be assessed beyond simple answers and easy fixes.

by Nina Bellucci Butler

Bio-based plastics will play a role in the path toward sustainability. As with most new developments though, integrating these new materials into popular usage will be complicated. From production of feedstock to end-of-life management, the trade-offs and impacts must be explored throughout a product's lifecycle.

Bio-plastics in the marketplace

Cellulose and starch polymers have been around for nearly a century, but their use in packaging applications has grown only recently, as they still face a steep growth curve in order to achieve significant market share. Synthetic biopolymers and polylactic acid (PLA) are being used in some plastic package applications, but are still in the early stages of commercialization.

Bio-based and biodegradable plastics comprise less than one percent of the global plastic market share. Consider current capacity for some of the largest U.S. bio-based resin producers (e.g., NatureWorks' PLA is slowly working toward 300 million pounds per year), as compared to the more than 100 billion pounds of plastic produced in the U.S. each year.

Cost and limited performance capabilities, compared to conventional plastics, have restricted the expansion of bio-based plastics. However, some bio-based resins recently have become cost-competitive with conventional resins. And technological developments, such as nanotechnology using silicon, may offer improved performance characteristics.

One of the great conundrums with bio-based plastic is the desire for the product to be two things often at odds with each other: Biodegradable, yet durable for the product's life. Nanotechnology may enable a plastic to perform during a product's life and then degrade at a specified time, but the impact of such nanoparticles on the environment is unknown.

Polyhydroxyalkanoates (PHAs) are the newest family of biopolymers to approach commercialization. Through a joint venture between Metabolix (Cambridge, Massachusetts) and Archer Daniels Midland (Decatur, Illinois), production of PHA is slated to be online in 2008. Like PLA, PHA is produced by fermentation; however, PHA is made inside a living bacterial cell. According to Metabolix, the material's properties range from rigid thermoplastics to highly flexible plastics. Metabolix plans to genetically modify crops, such as switch grass, to "grow" plastics, raising concern about cross polli-

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nation with non-modified plants.

New products from new feedstocks

Most bio-based plastic produced in the U.S. is made from corn, although some companies, such as Innovia (Tecumseh, Kansas) and Eastman Chemical (Kingsport, Tennessee), make cellulose film and acetate from trees and cotton. Other crops promise higher feedstock yield per acre, but corn remains the preferred feedstock at this time.

One acre produces about 10,248 pounds of corn annually (or 183 bushels). According to NatureWorks (Minnetonka, Minnesota), 2.5 pounds of corn is used to produce one pound of resin. Growing enough corn to produce all the resin consumed worldwide would require the landmass equivalent of about two or three mid-sized U.S. states (145,000 square miles).

The U.S. enjoys a surplus of corn, but demand for corn will undoubtedly increase as the world population grows, which is reflected in high corn future prices. Most beef cattle rely on corn-based feed, so rising beef consumption also impacts corn supply. Ethanol produced from corn is the other big variable.

Government policies, including subsidies, incentives or exemptions, will have a significant impact on the development and use of crops for fuel, feed and material feedstocks. The uncertainty surrounding these policies – and, by extension, how these policies will influence the marketplace – makes projecting the likely growth trajectory of bio-based plastics difficult.

Lifecycle issues

Beyond production limitations, the impact of conventional agricultural practices on the environment, including water contamination, soil erosion and greenhouse emissions, must also be considered. Corn production requires fossil resources for fuel, fertilizer and pesticides.

Many lifecycle analyses for plastics, including bio-based, are limited to analyzing the impact up to the point of resin pellet production. These studies do not take into account other factors, such as product performance, as it relates to feedstock material efficiency. If you simply need less of one material versus another to achieve desired product performance, then that should be factored into the LCA analysis.

End-of-life scenarios also have not been addressed. If one material has a higher possibility of being recycled, how does this affect the product's total greenhouse gas emissions? The complete lifecycle, from production of feedstock through a product's end of life, must be considered.

Identifying all of the lifecycle impacts does not necessarily lead to an easy choice, but at least the information necessary to make decisions that involve trade-offs is available. Are we willing, for example, to accept genetically modified crops if it enables the U.S. to use a material made from renewable resources?

End-of-life issues

As consumption grows and plastics replace other materials, plastic discards grow. Discarded plastic generally ends up in landfills, although an increasing amount is recycled or incinerated. Inaccuracies in reporting have many believing that landfills are clogged with plastic; however, according to the 2005 U.S. Environmental Protection Agency's (Washington) waste characterization study, most waste is organic material, such as wood, yard trimmings, paper and food scraps.

The general public finds degradability a positive attribute, and is attracted to bio-based plastics for its potential degradability. The reality is that landfills are built to prevent degradation, but most fail eventually. When material eventually degrades in the absence of oxygen, it produces methane, a potent greenhouse gas.

Further complicating matters, degradation often requires very specific conditions. Many bio-based plastics in the market only degrade at the high temperatures found in commercial food scrap compost facilities, so a switch to bio-plastics is not likely to solve solid waste or litter problems.

In terms of recycling, plastics are lightweight and often voluminous, which presents a challenge without densification capabilities for efficient collection and handling. Without significant supply of material, investment in recycling equipment is difficult to justify.

Most plastic packaging falls within six main types (No. 1 through No. 6), and each type exhibits a wide range of characteristics. Polyethylene terephthalate (PET) No. 1 bottles, for example, differ in material processing characteristics from PET No. 1 food trays. The variety of resins and the low tolerance for contamination among types are some of the reasons plastics have a low recycling rate. Consequently, the most developed reclamation infrastructure for post-consumer plastic materials exists for the largest plastic packaging categories: Containers (primarily bottles) and film (e.g., bags and pallet wrap).

PLA bottles represent a threat to the well-developed PET container recycling infrastructure. Because both PLA and PET sink in water (the PET recycling system uses a float/sink tank to separate the polypropylene lids from the PET bottle), the materials are difficult to separate. PLA also melts at a lower temperature than PET and is a contaminant to the PET stream. Near infrared (NIR) technology helps some processors sort out contaminants, such as polyvinyl chloride (PVC) and potentially PLA, but this technology is not foolproof and not all facilities can afford the investment.

Of course, manufacturers of bio-plastics are looking to enter the film and container markets because they represent the biggest opportunity for growth. However, indiscriminate use of bio-based plastics in bottle and film applications may severely disrupt the well-developed recycling infrastructure for plastic bottles and film (e.g., plastic bags), which have a collection system. The annual recovery of conventional plastic through the established collection and reclamations systems far exceeds the global production of bio-based plastic.

At this time, plastic bottles made with PLA have few good end-of-life options. Too few PLA bottles are produced to warrant economically feasible separation measures at material recovery facilities (MRFs), no reclamation infrastructure exists and very few municipal compost systems accept PLA bottles. Non-bio caps, rings and labels further complicate the compost option. Regrettably, most packaging ends up in landfills and most bio-based packaging will likely end up there, too.

Identifying critical packaging attributes

To illustrate the trade-offs in switching from conventional plastics to a bio-based plastic, consider the bottle application, which has created significant controversy in the recycling community. A handful of companies are bottling beverages, such as water or milk, in PLA rather than in conventional plastics. One of the challenges is that the PLA bottle

Defining the terminology

Bio-based – Plastics produced using carbon that comes from contemporary (non-fossil) biological sources and may or may not be biodegradable. Carbon 14 signature quantifies bio-based content.

Biodegradable – Biodegradable plastics are limited to plastics that convert to carbon dioxide, water and biomass through microbial digestion. They may or may not be bio-based. The American Society for Testing and Materials (West Conshohocken, Pennsylvania) has standards for bio-based and biodegradability.

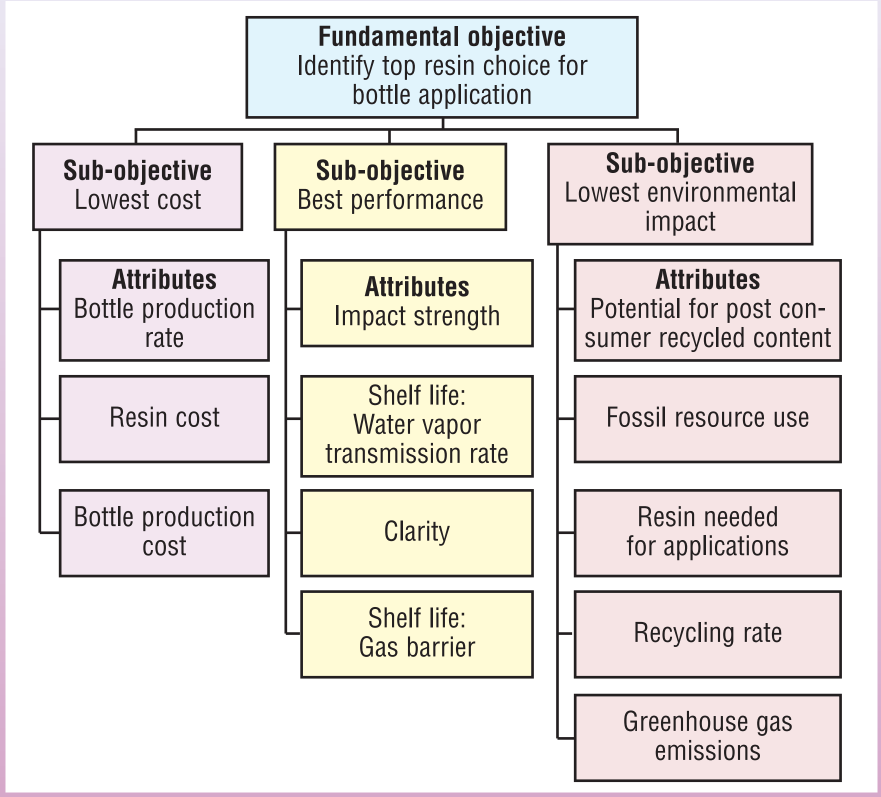
Biopolymer – Biopolymer is a term that includes bio-based and some biodegradable plastics, as well as non-plastic material, such as proteins, lipids and DNA. Polylactic acid is a biopolymer that also is a bio-based and biodegradable plastic.

Table 1 Weights on sub-objectives

	Weight score
Environmental organizations	
Environmental impact	4.50
Performance	0.30
Cost	0.25
Industry	
Environmental impact	0.34
Performance	0.33
Cost	0.32

Source: Moore Recycling Associates Inc., 2007.

Figure 1 Hierarchy chart of packaging criteria



Source: Moore Recycling Associates, Inc., 2007.

looks very similar to the PET bottle, but cannot be recycled with PET. As mentioned previously, PLA's presence in PET bales creates processing challenges for PET reclaimers. To understand the dilemma in more detail, consider the following case study that compares PLA to three other conventional plastics in the bottle application.

Within the bottle application, best resin choice serves as a fundamental objective. Since performance and cost are the two most commonly discussed aspects of packaging, and with environmental impact becoming a more significant aspect of packaging, three natural sub-objectives emerge: Lowest cost, best performance and lowest environmental impact.

To identify the most important packaging attributes within these sub-objective categories, key stakeholders were surveyed. Respondents included the for-profit sector, including directors of packaging or government affairs for brand owners, trade associations, retail companies and resin manufacturers, while the not-for-profit sector consisted of environmental advocacy organizations.

The respondents rated the three sub-objectives between one and 10, with 10 indicating the highest level of importance in contributing to a superior plastic bottle. They also rated a selection of plastic bottle attributes under each of the three broad categories between one and 10. Packaging criteria that received consistently lower rates were omitted. The hierarchy chart in Figure 1 was developed from the survey of stakeholders. Both groups rated environmental impact highest, then performance and cost last. The environmental organizations showed more disparity between cost and environmental impact. Table 1 illustrates the rates given to each sub-objective by sector.

How much does one attribute matter compared to another?

The multiattribute utility theory (MAUT) is designed to address trade-offs among multiple goals to achieve an overall goal. MAUT allows a decision maker to explore two or more alternatives. Each alternative may have multiple characteristics, or measurable attributes, that contribute to the decision process. Using a simple method like MAUT enables a decision maker to modify data or other inputs with ease and transparency.

MAUT assesses the relative priority the decision maker places on one sub-objective over another and on one attribute over another. This value is referred to as the weight. The weight given to an attribute reflects the willingness to trade one attribute for another to achieve the fundamental objective.

For this analysis, proportional scoring was used, which relates data internally using best or worst values per category. This scoring method assumes a risk-neutral attitude toward the final decision. Once data is normalized, each value is referred to as a score (U). Below is the equation for proportional scoring:

$$U(x) = (x - \text{worst}) / (\text{best} - \text{worst})$$

The decision maker usually knows the scores and alternatives before determining weights, but for the sake of capturing the views of a wide audience, the process of eliciting weights was simplified. Ideally, a decision maker goes through a rigorous process to elicit true preferences (weights). In order to determine weights for each sub-objective and attribute for the survey respondents, each key stakeholder's rating was divided by the sum of all rates in the category, so that the weights sum to one. To capture all of the respondents' preferences, all the weights were averaged yielding one value for each sub-objective and each attribute.

Evaluation of the alternatives

Once the weights and scores were identified, the next step was to calculate the overall utility of each alternative. The plastic bottle types selected for analysis were:

- Injection stretch-blown polyethylene terephthalate (PET #1)
- Extrusion blow-molded high-density polyethylene (HDPE #2)
- Extrusion blow-molded polypropylene (PP # 5)
- Injection stretch-blown polylactic acid (PLA #7).

Many resins are used to make plastic beverage bottles, but the two most commonly used conventional resins (HDPE and PET), as well a third resin (PP) that is picking up market share, were used. Polylactic acid is the only bio-based plastic resin currently used in bottle applications.

Table 2 illustrates all of the attributes and corresponding scores, weights and the four alternatives. Each score multiplies the product of the sub-objective weight and the attribute weight. The sum of the product of each score and combined weight within each alternative yields the overall utility. A higher utility indicates a more favorable choice.

Bottle data and preferences are subject to change. In fact, some data in the environmental section are debatable since it represents production only to the point of the resin pellet rather than the bottle, and does not take into account the amount of resin used in the production of a bottle. PET has the highest utility, indicating that PET is the most favorable choice given the preferences of those surveyed and the data available. Performance scores contributed the most to PET's overall utility.

Modifying weights or bottle data will demonstrate sensitivity. For example, what scores would have to improve for PLA to surpass PET? Given the current set of data, PLA's cost and performance scores would have to catch up to those of PET to achieve a higher overall utility, but at what environmental cost? Only a dramatic shift in weights could push PLA ahead at this time.

Figure 2 offers another view of how weights and scores contribute to the overall utility.

Table 2 Comparison of four plastic beverage bottles

Characteristic	Weight	Units	HDPE	PET	PLA	PP
Environmental impact	**0.40**					
Greenhouse gas emissions	0.21	Tons per 100 year CO^2 equivalent per ton of resin	2.10	2.30	1.20	1.80
Score			*0.18*	*0.00*	*1.00*	*0.45*
Recycled content	0.20	Potential for post-consumer content	no	yes	no	no
Score			*0.00*	*1.00*	*0.00*	*0.00*
Fossil resource use	0.20	Tons of FRU per tons of material	0.94	0.94	0.86	1.00
Score			*0.43*	*0.43*	*1.00*	*0.00*
Resin needed for application	0.20	Density of resin used for bottles (gm/cm^3)	0.97	1.37	1.24	0.93
Score			*0.91*	*0.00*	*0.30*	*1.00*
Recycling rate	0.19	Percent	0.29	0.23	0.00	0.05
Score			*1.00*	*0.80*	*0.00*	*0.17*
		Environmental utility	***0.197***	***0.177***	***0.187***	***0.130***
Performance	**0.30**					
Shelf life: Gas barrier	0.26	cc-ml per m^2 per 24 hour atmosphere	150.00	10.00	60.00	200.00
Score			*0.26*	*1.00*	*0.74*	*0.00*
Impact strength	0.25	Elmemdorf tear strength	120.00	2,600.00	64.00	600.00
Score			*0.02*	*1.00*	*0.00*	*0.21*
Shelf life: Water vapor transmission	0.25	gm-ml per m^2 per 24 hour atmosphere	1.00	2.00	23.00	1.00
Score			*1.00*	*0.93*	*0.00*	*0.99*
Clarity	0.24	Level of haze	1.00	3.00	3.00	2.00
Score			*0.00*	*1.00*	*1.00*	*0.50*
		Performance utility	***0.097***	***0.295***	***0.130***	***0.126***
Cost	**0.30**					
Resin cost	0.34	Dollars per pound	0.59	0.70	0.75	0.69
Score			*1.00*	*0.31*	*0.00*	*0.38*
Bottle cost	0.34	Dollars per 1,000 bottles	68.00	62.00	70.00	81.00
Score			*0.68*	*1.00*	*0.58*	*0.00*
Production rate	0.32	Pounds per hour per machine	436.22	1,811.99	1,700.00	370.20
Score			*0.05*	*1.00*	*0.92*	*0.00*
		Cost utility	***0.176***	***0.231***	***0.148***	***0.038***
Overall utility			**0.470**	**0.702**	**0.465**	**0.294**

Source: Moore Recycling Associates Inc., 2007.

Drawing conclusions

While the results of the case study above are interesting, the more important outcome is the illustration of the elements in the decision. Data, preferences and alternatives will change as new materials emerge, and as more up-to-date data surfaces.

Performance, however, cannot be ignored. A package that fails to withstand impact during shipment creates waste, which is costly – both environmentally and economically. Cost of the bottle affects the price of the consumer product, which makes cost another important element since consumers are often price sensitive. If political or technical developments improve manufacturers' access to bio-based plastics, with costs and performance comparable to conventional plastics, then the need for more robust approaches to weighing environmental trade-offs will grow. Furthermore, these approaches need to keep reduction of greenhouse gas emissions, along with source reduction and conservation, as top objectives.

Unfortunately, not all biodegradable plastic packaging is made with 100-percent bio-based plastics. According to Brenda Platt of the Institute for Local Self Reliance (Washington), all commercially available, compostable plastic shopping bags contain some fossil-resource-based material. This blended material is a serious contaminant to plastic bag recycling programs, thus raising some concerns among composters.

Is there a future for bio-based plastics?

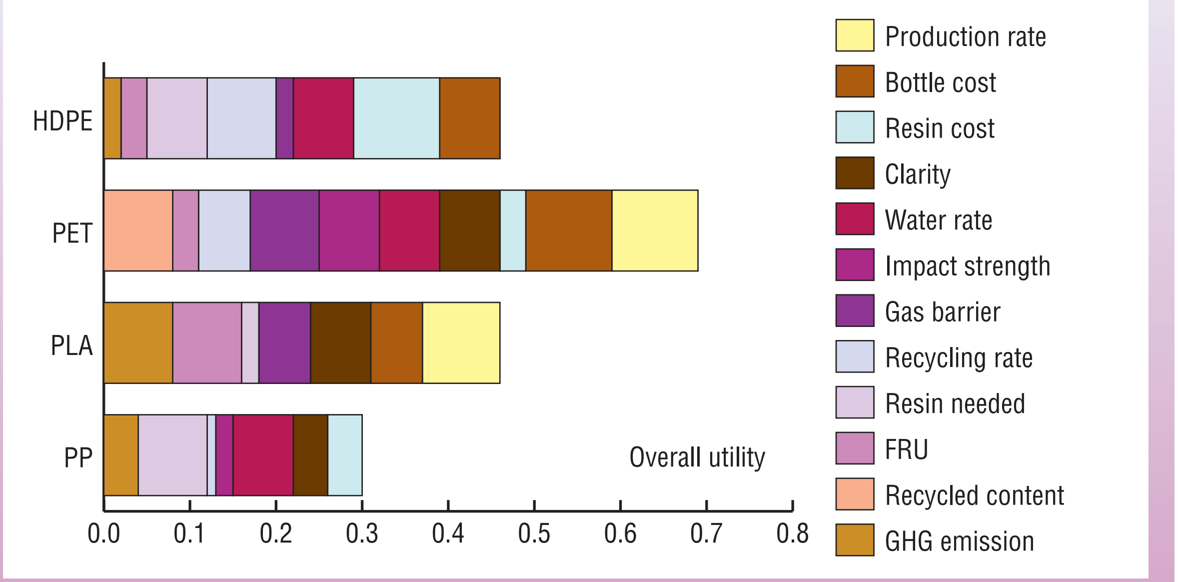
PLA bottles in the marketplace are 100-percent bio-based, but currently have few good end-of-life options. Bio-plastic packaging remains a long way from reaching the critical mass necessary to cost-effectively recover the packages through curbside recycling programs. The PVC, PP and PET bottles with barriers are examples of materials that lack the critical mass for recycling.

Perhaps more take-back programs, such as the drop-off programs at some Wild Oats Markets (Boulder, Colorado), could facilitate recovery of bio-plastic packaging. Of course, such programs will depend on significant growth in the composting infrastructure. Perhaps the much needed growth depends on clearly labeled, compostable plastic in food service applications that could carry food scraps to compost facilities. Currently, composters are ending up with recyclables and recyclers are ending up with compostables.

Bottles and film are very large markets for plastics, but risk significant disruption of existing recovery systems. The potential for bio-based plastics extend well beyond bottles and film, and even into the non-packaging world. Some truly exciting developments involve bio-based plastics in durable applications (e.g., computers or cellphones) that might displace flame retardant materials. Clothing, other fiber applications, electronics and anything not readily reusable or recyclable also offer huge potential – all without the worry of disrupting existing plastic recycling systems.

Continued consumption at an unsustainable rate, merely displacing one material for another, may make us feel better, but will not solve the actual solid waste challenges. Unfortunately, bio-based plastics are not an environmental panacea, but rather another avenue to explore for living in a sustainable way. **RR**

Figure 2 Contribution of attributes' values and weights to overall utilities



Source: Moore Recycling Associates Inc., 2007.

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