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EDITORIAL

Commentary: The Relationship Between "Biobased," "Biodegradability" and "Environmentally-Friendliness (or the Absence Thereof)

Douglas G. Hayes[1]

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Dear Editor

I am surprised at how many instances I have encountered as reviewer and editor for *JAOCS* and other journals, in reviewing of proposals, as an educator at a major US university, and in conversations with the general public at the high level of misunderstanding that exists with regard to the terms "biobased," "biodegradable," and "environmentally-friendly." In addition, I have encountered several instances where a relationship has been proposed between two of the three that was incorrect. As I will discuss below, no such relationships can be assumed, and any such relationship needs to be properly supported. I believe this discussion will be of value to prospective authors and practicing scientists.

Biobased refers to a substance's "beginning-of-life", i.e., that it is "… derived from plants and other renewable agricultural, marine, and forestry materials and provide an alternative to conventional petroleum derived products," per the definition provided by the USDA BioPreferred Program [1]. To illustrate, I use the example of a 12-hydroxystearic acid diestolide ester derivative depicted in Fig. 1, which is a potentially valuable lubricant material. This product can be prepared from biobased or fossil fuel-based resources in part or in whole. Most commonly, the product would be prepared from 12-hydroxystearic acid, derived from castor oil via hydrogenation, and acetic acid and 2-ethylhexanol, derived from petroleum. However, acetic acid is a common product from fermentation, and a biobased route for production of 2-ethylhexanol has been recently reported [2]. The biobased content of a product is determined by calculating the percentage of its carbons derived from renewables. For this situation, 36 carbons are from renewables (12-hydroxystearic acid groups) and 10 carbons (i.e., the 2-ethylhexyl and acetyl groups) are not. Therefore, the biobased content is $36/46 \times 100\%$, or 78%. (If the origin of the product's feedstocks are unknown, the biobased content is determined by measuring the product's stable carbon isotope profile, per ASTM D6866 [3]. In this editorial, I will refer to ASTM standards and testing methods, but note that equivalent documents and procedures are available through ISO and other standardization organizations. The value of a product being biobased compared to fossil fuel-derived is that it would not generate atmospheric CO_2 over its lifecycle; moreover, the amount of CO_2 generated from its end-of-life (e.g., by aerobic biodegradation or incineration) is approximately equal to the amount of CO_2 taken up by plants or microorganisms that provide the product's feedstocks ("carbon–neutral"). In contrast, CO_2 produced from the end-of-life of non-biobased products would not be readily recycled into the formation of new fossil fuels, leading to a net increase in atmospheric CO_2, a greenhouse gas associated with climate change.

In contrast, *biodegradability* refers to the breaking down of a product via microbial activity (e.g., by aerobic catabolic pathways, producing CO_2, water, and biomass as end products, or anaerobically, producing CO_2 and CH_4), a product's "end-of life." Plastics labeled as 'biodegradable" should be compliant with standards documents, such as ASTM D6400 (D6868), biodegradability of plastics (products that contain plastics) under aerobic industrial composting conditions, or D7801, biodegradability in marine environments [4–6]. In ASTM D6400, specific criteria are listed for macroscopic disintegration, inherent biodegradation, ecotoxicity, and heavy metal content to be achieved by the plastic and its major constituents, with each criterion evaluated using

✉ Douglas G. Hayes
dhayes1@utk.edu

[1] Department of Biosystems Engineering and Soil Science, University of Tennessee, 2506 EJ Chapman Drive, Knoxville, TN 37996-4531, USA

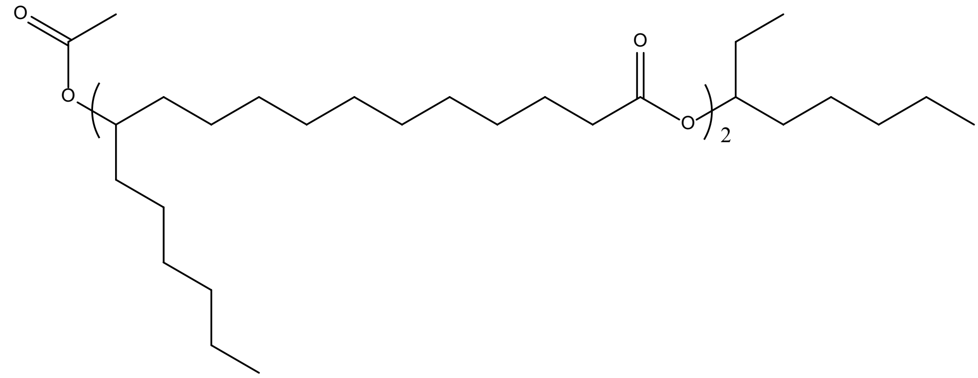

Fig. 1 Molecular structure of a diestolide of 12-hydroxystearic acid "capped" with acetyl and 2-ethylhexyl end groups

standardized tests [6]. For example, ASTM D6400 specifies that 90% of the plastic's carbons are oxidized to CO_2 within 180 days using a standardized laboratory test, ASTM D5338, which is operated under conditions that mimic industrial composting [6, 7]. Total biodegradation is not used as a criterion since the conversion of the product's carbons into biomass can reach 10%. For ASTM D7801, criteria are based on standardized tests that mimic the marine environment [4].

The environment plays a key role in the rate and extent of biodegradation; for example, polylactic acid, $H[OCH(CH_3)CO]_nOH$, is readily compostable (58 °C), but not biodegradable under ambient conditions (25–30 °C), due mainly to its possession of a glass transition temperature near 50 °C, meaning that at temperatures <50 °C, the polymers are tightly packed. In summary, "biodegradability" is an ambiguous term unless (1) the biodegradation environment is specified (e.g., "industrial composting conditions") and (2) compliance with a standard (e.g., ASTM D6400) is met. The standard will specify the biodegradation level to be achieved and the time required for it to be achieved.

Environmentally-friendly is a related, but even more ambiguously defined term, referring to the absence of environmental harm, and should be referred to either the process for making the product, the product itself, or the entire life cycle of the product (from cradle to grave, but with more emphasis on the latter stage). For a product to be considered "eco-friendly," it should minimally be supported by compliance to a related standard, such as one of the biodegradability standards listed above (which include criteria for ecotoxicity and other properties, in addition to biodegradability). For lubricants such as the one depicted in Fig. 1, standards are specified by several different organizations such as Blue Angel (Germany), the European Eco-label, or OSPAR, which contain standards on biodegradability, aquatic toxicity, and bioaccumulation assessed using standardized tests [8]. One could say their product is an "environmentally acceptable lubricant according to OSPAR specifications," e.g. For these standards, some of the organizations have specific requirements for primary and ultimate biodegradation (e.g., Eco-label), where the former refers to the depolymerization, to produce monomers or other small building blocks, and the latter to full microbial conversion. Standards exist of other types of products as well, specified by governments or standardization organizations.

A common mistake in many written scientific results is the equating of "biobased" to "biodegradable" or "eco-friendly". Moreover, a product's beginning- and end-of-life are often uncoupled. I will now provide examples to support this statement.

- Biobased products are not necessarily biodegradable. Factices are cross-linked compounds employed in rubber products that are prepared from seed oils through vulcanization. Factices are not readily biodegradable [9]. Another example is "green diesel," which although being biobased, like other alkanes are poorly biodegradable.
- Many fossil fuel-derived materials possess good biodegradability. Examples include polyesters such as polycaprolactone or polybutyrate adipate terephthalate (PBAT).

These examples illustrate that biodegradability is an inherent property of the product's molecule: ester bonds are readily hydrolyzed by microorganisms and cross-linkages reduce biodegradability. In addition, hydrocarbons are poorly biodegradable. For example, the poor biodegradability of polyethylene terephthalate (PET) has contributed to the accumulation of micro- and nano-plastics in marine ecosystems, harming fish and other organisms, independent of whether the PET was derived from fossil fuels (per conventional technology) or from renewable resources (plant-bottle™) [10].

Biobased should not be directly associated with eco-friendly. Although biobased materials' beginning-of-life is more environmentally-friendly than fossil fuel-derived materials, the emphasis on eco-friendliness should focus more upon the end-of-life or the entire lifecycle of a material.

In summary, the terms biobased and biodegradable need to be used using great care, keeping in mind their specified definitions, the support of their use via standards, and that they refer to the beginning- and end-of-life of a product, respectively, which are often independent of each other. Environmentally-friendly is a somewhat ambiguous term that focuses mainly on the environmental impact of the product's end-of-life.

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