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MATERIAL DERIVATION AFFECTS THE PERCEPTION OF SUSTAINABILITY IN POLYMER PRODUCTS

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ABSTRACT

There is an increasing demand for "natural" products by consumers, businesses, scientists and product developers. Trends suggest that the term *natural* may be colloquially understood to be a plant-based material or ingredient. This study investigates whether this trend could apply to polymers by declaring the derivation of the polymer as a plant or as petroleum. Because polymer materials do provide environmentally positive attributes for products in relation to other materials, such as lightweighting, durability, and lower fabrication energy requirements, it may be helpful to understand the influence of a polymer's derivation on the perception of a polymer product's sustainability. The goal of this study is to assess peoples' relative perceptions of the sustainabilities of polymer drinking cups when the base materials from which the polymers were derived are exposed. A set of six injection-molded drinking cups was given to research subjects to analyze. Each cup is made of a different polymer. The polymers have derivations including petroleum, corn, sugar and trees. Participants evaluated the cups on six qualitative design strategies for sustainability, including natural-ness. This paper compares the perceived sustainable attributes of the cups, and which attributes were most strongly influenced by revealing the derivation of the polymers.

Keywords: *sustainable polymer selection, sustainable design strategies, natural materials*

1 INTRODUCTION

Sustainable design plays an essential role in negating and reversing the effects that consumption has had on our natural and built environments. Concern about sustainable development and climate change has caused people to attend to and alter the ways they live to

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support environmental goals and ensure that future generations can meet their own needs (Pew Research Center, 2020; United Nations, 1987). Product designers invested in this movement aim to design products that are both perceived to be sustainable by consumers and are measured to be sustainable by scientific metrics.

One observation in this environmental movement is that the demand for more "natural" products in peoples' health and homes is increasing (Mintel, 2021a and 2021b). While this trend may be caused by the desire to be more sustainable, natural materials are not necessarily less environmentally impactful. Moreover, "natural" is an ambiguous, broad and minimally regulated category. Dictionary definitions for natural refer to having the characteristics of nature or coming from nature (Brittanica, 2022; Merriam-Webster, 2022), a definition which ultimately applies to every material humans have harnessed. Science journal articles and books refer to natural materials predominantly as substances that come from plants or animals (Kumar, 2020; Lee, 2014; Muthu, 2020; Patwa, 2018; Ritchie, 2014; Willför, 2008), but notably also include minerals (DeMouthe, 2006). The US Food and Drug Administration requested comment on the use of the term "natural" as related to food in 2015 (The Federal Register, 2015), prompted by requests for more specific regulation of the word in food product descriptions. No new FDA requirements have yet come to fruition resulting from the comments collected. Consumers, scientists and regulators don't have consistent definitions or even understandings for "natural" material attributes or requirements, but collectively use the term "natural" as one that is important to define the materials we use.

Product designers also do not have a succinct definition of a natural material, despite the fact that selecting natural materials is one of the principal strategies for sustainable product development (Graedel, 1995). Just like consumers, scientists and regulators, product designers assume that the materiality of a product is an indicator of that product's overall sustainability (Ashby, 2009). The material an object is made of is not the sole indicator of a calculated environmental impact, however. The Okala (White, 2013), Sustainable Minds (Sustainable Minds, 2022) and Eco-indicator 99 (PRé Sustainability, 2000) Life Cycle Assessment tools for products weigh the materials used in a product, but also weigh the fabrication techniques, transportation of the product, the energy consumed in the product's lifespan and the end of product life. While quantitative sustainability measurements can be conducted through Life Cycle Assessments (LCA), the perceptions that consumers and designers have of material sustainabilities are not necessarily the same as what is calculated in an LCA. For example, assuming comparable size, an aluminum water vessel may be perceived to be more environmentally friendly than a high density polyethylene (HDPE) water vessel despite the fact that an LCA may indicate that an aluminum vessel would have a higher environmental impact than an HDPE vessel (Muenchinger, 2013). Gaining a deeper understanding of user attitudes towards sustainable products can assist the success of environmentally conscious new product design (Hojnik, et al., 2019).

Studies of consumer perception of product sustainability have indicated that natural-ness is a driver of whether a product is considered sustainable as a whole (Muenchinger, 2014; Muenchinger, 2013) and that materials in products categorized as "natural" were warm, rough, heavy, and not transparent or reflective (Karana, 2012). Polymers do not instinctively fit into any

of the descriptors of the Karana study, and are a primary material category for consumer products. Understanding the emotional relationship that polymers do or can have with the descriptor "natural" would benefit designers, marketers, and even consumers in combined efforts to be more environmentally conscious in product choices. Because Kansei studies quantify the emotional responses people have to attributes of products (Nagamachi, 1995), and tease out perceptions that consumers may not know they have (Kang, 2011), a Kansei study was conducted to examine the effect of participants knowing the derivations of polymers used to make drinking vessels. The hypothesis is that the more plant-based polymer derivations would skew the perception of "Natural" to be stronger, and that the overall perceived sustainability of the material would be higher than for petroleum-based polymers. The goal of this study, as of other Kansei studies (Nagamachi, 2002) is to guide designers in developing products that consumers emotionally connect with as having latent environmentally friendly attributes.

2 METHODS AND MATERIALS

Two hundred seventy-six people participated in the Kansei cups ranking exercise, all associated with the University of Oregon. Two hundred seventy participants self-identified as students, fifty-seven percent self-identified as male and forty-two percent self-identified as female. Participation in the study concluded prior to a lecture about measuring sustainability and similar research studies in perceptions of sustainability. Financial compensation was not provided to the participants.

2.1 Cups

The cups used in this study were fabricated specifically for this research. They were made from six different polymers: high density polyethylene (HDPE) derived from petroleum, HDPE derived from sugar, polypropylene (PP) derived from petroleum, a composite of 30% cellulose derived from trees plus 70% PP derived from petroleum, polylactic acid (PLA) derived from corn, and a co-polyester (PES) derived from petroleum. They were all fabricated through injection molding using the same tooling. The cups are shown in Figure 1.

Figure 1. Six cups pictured left to right: HDPE sugar, HDPE petroleum, 30% cellulose/70% PP composite, PES from petroleum, PLA from corn and PP from petroleum.

While the vessels are made of different polymers, there is a goal to have the objects in the study be as similar as possible. All materials are their natural color; no colorants were used.

There are, however, noticeable physical differences in the cups due to the natural color, densities and shrink rates of the different materials. The PLA and PES cups are both transparent, but the PLA has an amber tint and the PES has a purple tint. The petroleum-derived HDPE is brighter white than the sugar-derived HDPE. The composite cellulose/PP is opaque amber with embedded lighter flecks. The weights of the cups range from 77g (both HDPE cups) to 108g (PLA), a 29% difference. Because the polymers have different shrink rates, the heights of the cups are slightly, though visibly different from polymer to polymer. The tallest cup is the PES at 96mm, and the shortest is HDPE (sugar) at 93mm, a 3% difference.

The impact factors for both the material and for the injection molding process (Okala impact factor for injection molding is 0.72 points/lb) are multiplied by the weight of material of the object to determine the total Okala Impact Factor points for the object. These impacts, for the materials and the product totals, are provided from lowest to highest total impact in Table 1.

Table 1: Cup materials, weights, Okala Impact factors and total points

Material	Weight in g (oz)	Okala Material Impact Factor in points/lb	Okala Impact Factor, Material + Manufacture (injection molding)	Percentage increase in Impact from HDPE (petroleum)
HDPE (petroleum)	77.1 (2.72)	1.7	0.411	0
HDPE (sugar)	77.7 (2.74)	1.7	0.414	0.73
PP	72.0 (2.54)	1.9	0.416	1.2
Cellulose/PP	88.2 (3.11)	1.9 (use PP)	0.50	22
PLA	108 (3.80)	1.9	0.622	51
Co-polyester	101 (3.55)	3.6	0.959	133

The cup with the lowest Okala impact is HDPE (petroleum). The cup with the largest impact is the co-polyester cup, which has a 133% larger Okala impact over the HDPE (petroleum) cup.

The cups were provided to the participants as a six-sample set with both a group-identifying letter (A-P) common to the set and a material identifying number printed on the bottom of each cup. The names and derivations of the materials were provided to study participants, such as "High Density Polyethylene (HDPE) derived from sugar".

2.2 Word Pairs

Participants in this study were asked to rank each cup on six word pairs designed to target qualitative strategies of sustainable design. The word pairs are: *Delicate – Durable; Lasting – Degradable; Raw – Finished; Harmless – Toxic; Natural – Artificial; Recyclable – Waste*. These word pairs were constructed to address historic sustainable material selection strategies (Graedel and Allenby: 240) (Lewis and Gertsakis: 86-87). These word pairs have been successful in

determining feelings of sustainability towards products in previous studies (Muenchinger, 2012; Muenchinger 2013b, Muenchinger 2014).

3 RESULTS

Each cup is summarized by the average rankings in Figure 2. For each of the word pairs the more environmentally friendly word of the pair is positioned at the "1" side of the ranking on the 1-7 scale and the legend on the right presents this word. There is a general trend that the cups made from polymers derived from plants are perceived to be more sustainable than the cups made with polymers derived from petroleum. Clearly, all of the polymer cups are perceived to be Durable.

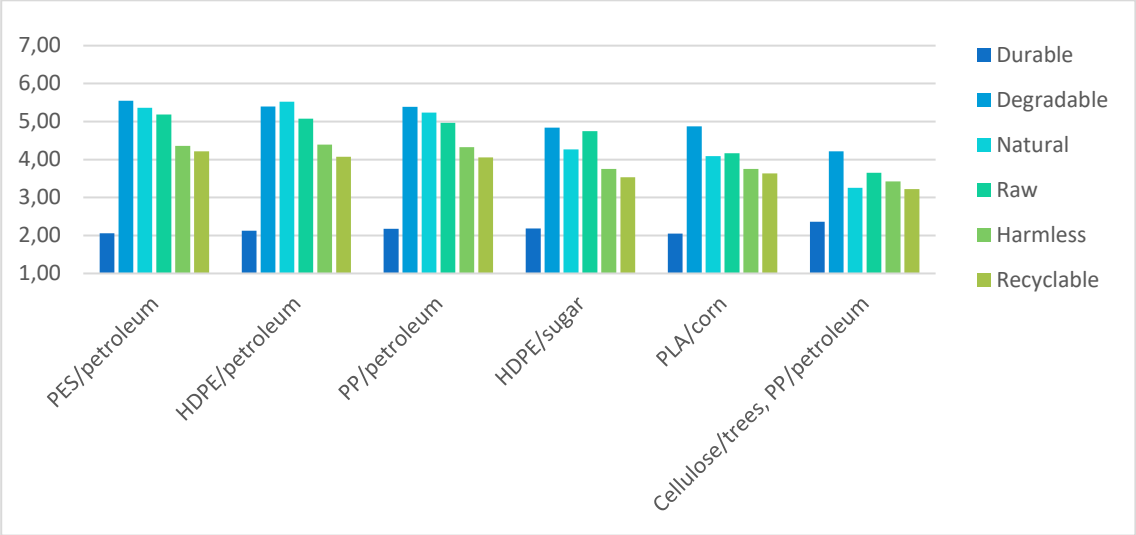

Figure 2. Average sustainability rankings of six polymer cups

4 DISCUSSION AND CONCLUSION

Visual representation of the data shows trends in perceptions of petroleum-based polymers compared to other polymer derivations, and perceptions of durability. The data in Figure 2 also suggests that the Cellulose/PP composite cup is perceived to carry the most complete set of characteristics associated with sustainability. For statistical significance comparing response data from the petroleum-based and sugar based HDPE cups, the Cellulose/PP composite cup, and durability factors of all cups, an alpha level of .05 was used.

4.1 HDPE: Petroleum-derived compared to Sugar-derived

The most direct comparison of cups for material derivation are the two HDPE cups. As is appropriate for cups made of the same polymer, they are the most similar of all the cup samples in weight, dimensional size, color, tactility and opacity. The average rankings of the HDPE cups are shown in Figure 3 for direct comparison.

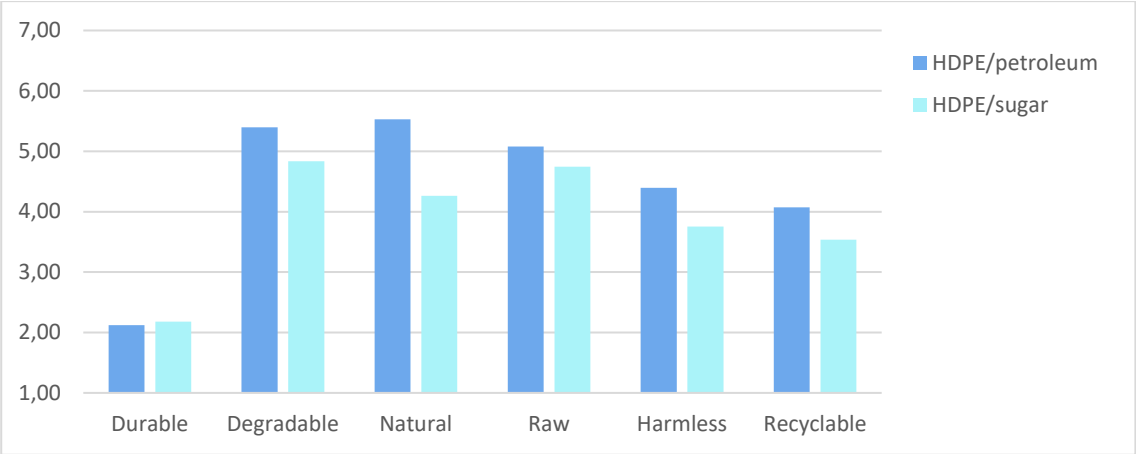

Figure 3. Average sustainability rankings of cups made from HDPE derived from petroleum and sugar

Five of the six word-pair rankings (Degradable, Natural, Raw, Harmless and Recyclable) show the sugar-derived HDPE cup to be perceived as more sustainable. Despite the variability of the responses, as indicated in the whiskers of the box plots in Figure 4, the perceived differences between the two cups in these five categories are statistically significant differences. The durable ranking, however, shows the petroleum-based HDPE cup to be perceived as more durable. This difference is not statistically significant, suggesting that the selection of a sugar-derived HDPE material would not negatively affect the perception of the product's durability.

Box plots of the data in Figure 4 show that the mean rankings for three of the six word-pairs (Degradable, Natural and Harmless) are lower for the sugar-derived HDPE cup, indicating stronger perception of sustainability. The responses are most tightly grouped, showing strongest consensus, that the HDPE cups are durable, not degradable, and not raw. Interestingly, it was common for the HDPE cup derived from petroleum to not be considered natural, while responses for the sugar-derived HDPE cup were more widely dispersed, yet provided a lower average ranking compared to the petroleum-derived cup and a significantly stronger overall perception of sustainability on that natural ranking.

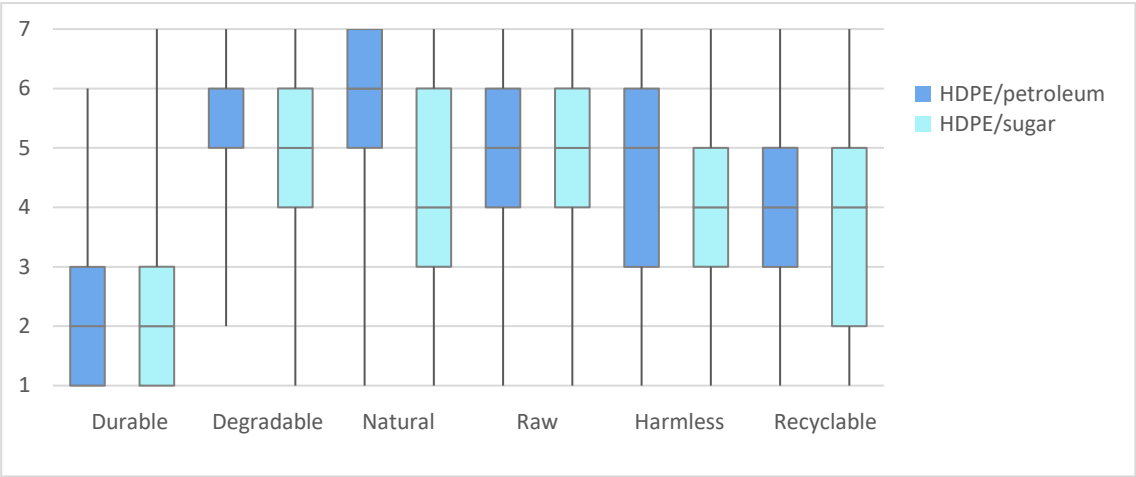

Figure 4. Box plot sustainability rankings of cups made from HDPE derived from petroleum and sugar

It is notable that the derivation, the stated difference between the two cups, influences perceptions of sustainability strongly. While the derivations are different, the molecular structure of HDPE is ultimately the same in each of these cups. Sugar-derived and petroleum-derived HDPE cups would be equally "degradable" and "recyclable." The "raw" term is as elusive as the "natural" term in definition and regulation, but it may be helpful to know that the sugar-derived HDPE cup does have a stronger perception of rawness. The "harmless-to-toxic" word pairing is meant to relate to the cup product, not the loaded environmental and social issues associated with mining and farming for material resources. As such, the two HDPE cups are equally "harmless." The perception of the sugar-based HDPE cup's natural-ness makes intuitive sense, as there are noted trends that natural materials are plant-based. The cups look the same, feel the same, smell the same, and they sound the same when tapped on a table. The senses do not provide enough information to influence perceptions of sustainability. Knowledge about the material derivation of the polymer is the source of the differences in perception. Therefore, describing the product's material as sugar-derived strengthens the perception of sustainability of the product.

4.2 Cellulose/Polypropylene composite

As seen in the general trends in Figure 2, the Cellulose/Polypropylene (PP) composite cup has the most sustainable rankings for five of the six word-pairs: Degradable, Natural, Raw, Harmless and Recyclable, compared to all of the other cups. Similar to the comparison between sugar-derived HDPE and petroleum-derived HDPE, the Cellulose/PP composite is perceived to be more sustainable than its peers. This is a statistically significant difference in comparison with all other cups in every category, with the exception of Durable, with every other cup. This composite is derived from 30% wood material, and 70% petroleum material, which is considerably less material from a plant-based and/or renewable resource than the other two plant-derived polymers: sugar-derived HDPE and corn-derived PLA, which are 100% plant-derived. Therefore, it must not be the derivation of the cup's material that is the driver of these perceptions.

The most obvious differences between the Cellulose/PP composite cup and the other cups are visual. It is a definitive opaque amber color, and the color is non-uniform. Qualitatively, it is not as shiny or reflective as the HDPE and PP cups. It is the median cup of the sample set in weight. Qualitatively, the tactility seems less lubricious than the HDPE and PP cups, perhaps toothier or fuzzier than the PES cup, and softer than the PES and PLA cups. Similar to the results in the Karana study, this cup is warmer and rougher compared to its set-mates, and is not transparent or reflective. The Cellulose/PP cups look and feel more like they've been made with a material that has grown though changes in seasons or weather, rather than one that has been perfectly mass manufactured.

4.3 Durability

Both the PLA and PES cups are perceived to be significantly more durable than the Cellulose/PP cup, but those are the only statistically significant differences the data show in perceived durability between the various cups. Two physical properties could prompt this difference in perceived sustainability: the mass of the cups/materials and the color and transparency of the cups/materials.

4.3.1 Mass

The two cups with the most mass, the PLA and the PES, had the biggest impression of durability. These two cups are heavier than the others by over 12 g, with PLA 50% heavier than the lightest PP cup, and PES 40.3% heavier than the PP. The cup perceived to be least durable, however, is the Cellulose/PP cup, which is not the lightest weight, rather is right in the middle of the set. The PLA cup is 22% heavier than the PP/Cellulose, and the PES is 15% heavier than the Cellulose/PP. It is interesting that the PES cup is petroleum-based, the PLA cup is corn-based and the Cellulose/PP cup is a mix of petroleum and plant, or more specifically, petroleum and trees. Based on these observations, it is hypothesized that the weight has a stronger influence on the perception of durability than the material derivation.

4.3.2 Color and transparency

The Cellulose/PP cup is the only cup of the set of six that has an inconsistent, mottled visual texture. The Cellulose/PP cup is opaque, like the two HDPE cups, and it has an amber hue. The PLA cup also has an amber hue. The PLA cup is transparent, as is the PES cup. As the two transparent cups are perceived to be the most durable, transparency is hypothesized to influence the perception of durability. It is notable, however, that this seems counterintuitive, as a widely known transparent material: glass, is known to fracture easily compared to other materials. As the Cellulose/PP cup is the only visually textured cup, inconsistent color may negatively influence the perception of durability.

Based on the direct comparison of the two HDPE cups, exposing a plant-based base material used to make a polymer does positively impact the perception of sustainability of the end product. This is a benefit to selecting and supporting the plant-based polymer industry in an effort to create, produce and sell more sustainable products. As there is no statistically significant difference seen by exposing plant-based polymer derivations in the perception of durability, which is an undoubted characteristic of polymer products for sustainable goals, there is not a downside apparent from this study. Other characteristics of color, visual texture and tactility should also be considered in polymer products when considering a consumer's perception of sustainability. Visual texture and tactility may be affected by in-mold texture application in injection-molded parts. Warm colors, or colors associated with plants may also affect the perceived sustainability of a product, and may be added as colorants to base polymers. In maintaining the goal of developing truly sustainable products, the qualitative strategies of exposing a plant-based material, application of texture and inclusion of color should be used in combination with quantitative metrics, such as LCA's to ensure that products are developed to have the least impact on our environment.

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