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Comparison and Analysis of Flexibility for Cutlery Made from Biobased/ Biodegradable and Petrochemical Materials

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Abstract

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Disciplines

Biology and Biomimetic Materials | Bioresource and Agricultural Engineering | Natural Resources and Conservation | Polymer and Organic Materials | Sustainability

Comments

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He currently works at Iowa State University as a Professor in the department of Agricultural and Biosystems Engineering. His research group focuses on using high power ultrasonics to enhance biofuel production as well as on using plant proteins for biorenewable, biodegradable plastics and composites. He is the instructor of courses that focus on manufacturing processes, materials for industrial technology, applied math for technology and a design/technology project study abroad experience in Taiwan.

Dr. Grewell is the Director of the NSF Center for Bioplastics and Biocomposites, is the Chair of the Biopolymers & Biocomposites Research Team, a Board Member of the Ultrasonic Industry Association, Society of Plastics Industry and Society of Plastics Engineers. He also has a position at the University of Erlangen in Germany and is Fellow of the Society of Plastics Engineers.

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ABSTRACT

Biorenewable plastics can have the potential to reduce pollution, demand on landfills, and dependence on foreign petroleum caused by petroleum-based plastics. To determine the performance of biobased utensils compared to petrochemical based utensils, this study investigated 13 bio-based/biorenewable utensils and six petrochemical utensils in terms of weight, stiffness, and specific stiffness (stiffness/weight ratio). The Commercial Item Description (CID), which was created by the U.S. Government via the General Services Administration (GSA), is the current standard for testing utensils. The biobased products selected for this study were "commercial or industrial products (other than food or feed) that are composed, in whole, or in significant part, of biological products, renewable agricultural materials (including plant, animal, and marine materials), or forestry materials." (USDA Bio Preferred Program, 2012). The results of this study show that the majority of biobased products exhibited similar strength and deflection under a given load as petrochemical products. This is the first comparison of this kind and it will allow designers and manufacturers to further optimize their products.

INTRODUCTION

With rising concerns about the environmental impact that can be attributed to petroleum-based plastics, several studies have looked at the effects these materials have already had on the environment and how future undesirable environmental changes can be avoided (USDA Bio preferred Program, 2012; Andrady, 2009). In addition, the use of renewable feedstocks strengthens the nation's economy by promoting agriculture and related industries.

Biorenewable resources can reduce a variety of environmentally hazardous materials, such as particulate matter, sulfur, carbon dioxide, and carbon monoxide. There is a general desire in the United States to reduce emissions and dependence on foreign materials by using renewable feedstocks. Executive Order 13514 "Federal Leadership in Environmental, Energy, and Economic Performance (EO 13514)", signed in October 2009, requires the Federal Government to be a leader in sustainability and environmental impact reduction. Cafeterias and food services within the government have been identified as an area of opportunity for sustainability initiatives, and disposable cutlery has been identified as potential applications for recyclable or compostable alternatives (United States Department of Agriculture, 2010).

The BioPreferred Program, established in 2002 as a result of the Farm Security and Rural Investment Act of 2002 and later expanded to reflect the requirements of EO 13514, helps guide the U.S. government in the purchase of products made from biorenewable materials. One of the BioPreferred Program's focus areas is product labeling. The USDA (United States Department of Agriculture) "certifies and awards labels to qualifying products and companies to increase consumer recognition of biobased products" (United States Department of Agriculture, 2010). The second focus area is to provide guidance in the federal procurement preference, which requires federal agencies to purchase biobased products when they come at similar costs and exhibit similar performance as their non-renewable counterparts.

Through a cooperative agreement with the USDA researchers at the Iowa State University Center for Industrial Research and Service (CIRAS) investigated biobased products to compare biobased and petrochemical cutlery/utensils in terms of strength/stiffness, and to determine biobased content in biobased disposable cutlery/utensils. The General Services Administration (GSA) (USDA Bio preferred Program, 2012) Commercial Item Description (CID) A-A-3109B "Fork, Knife, and Spoon, Picnic (Plastic)" specifies performance criteria to which disposable cutlery must adhere in order to be eligible for federal purchase. Specifically, CID defines maximum deflection of utensils under load. CIRAS tested biobased and petrochemical-based cutlery products with respect to these specifications.

Objectives of this work were to determine whether biobased utensils meet the flexibility specifications defined by CID, to compare the relative performance in terms of strength and stiffness of biobased and conventional (petrochemical based) disposable utensils, and to validate finite element models for utensil deflection. For the purposes of this study, biobased utensils were defined as any commercially available disposable utensils composed in whole or in significant part of agricultural (including plant, animal, and marine materials) or forestry materials. Conventional utensils were defined as produced entirely of non-biobased materials (United States Department of Agriculture, 2001).

The GSA states that each type of utensil (fork, knife, and spoon) must meet certain deflection requirements as detailed in Table 1. Any deflection exceeding the value given in Table 1 results in failure of the product. The standard also provides details on the type of loading and gripping during testing: in general, a 4.44 N load is applied near the tip of the utensil while the utensil is secured approximately in the middle of the handle.

TABLE 1: GSA - ALLOWED MAXIMUM DEFLECTION

Utensil	Maximum deflection (mm)
Fork	22.2
Knife	38.1
Spoon	25.4

In addition to the tests reflecting GSA standards, a similar study determined whether biobased utensils meet the flexibility specifications defined by CID and compared the relative performance in terms of strength and stiffness of biobased and conventional (petrochemical based) disposable utensils. While utensil manufactures often test their products' deflection, they do not commonly test their product with respect to the CID GSA standard. While metal and biobased utensils have been compared in the past (Treger et al., 2010), there are no articles comparing petrochemical to biobased utensils. In addition, while there are a number of journal articles on bioplastics and petrochemical plastics (Stevens, 2009, Lorcks, 1998), there are no studies that compare the performance of utensils made from these.

Although there are published results of Finite Element Analysis (FEA) on metal cups (Pegada, 2002) there are no published FEA results for biobased utensils, a key finding of this paper.

EXPERIMENTAL PROCEDURES

The procedures for testing the utensils were based on Commercial Item Description (CID) as detailed in its Section 5.2.1 for determining flexibility (US General Services Administration, 2006). In general, the standard details the requirements for loading and clamping locations as well as the loading levels and measurement locations in order to characterize deflection of utensils.

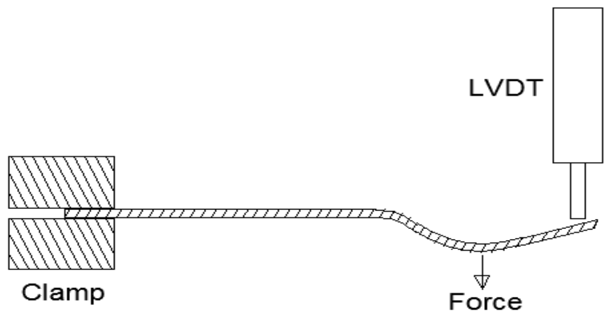
SAMPLES

Thirteen biobased utensils (spoons, forks, and knifes) and six petrochemical utensils in various styles were purchased from different manufactures. Availability determined the number of manufactures/styles for each material type. Products were designated by randomly assigned letters to ensure companies of the confidentiality of information regarding their products. The petrochemical utensils were categorized into two groups: those made from polystyrene and those made from polyethylene. It is important to note that this study only evaluated the performance of the utensils at room temperature. The effect of temperature was not determined in this study.

EQUIPMENT

Following the Commercial Item Description A-A-3109B standard (including calibration) the experimental setup was constructed as depicted in Figure 1.

FIGURE 1: DIAGRAM OF EXPERIMENTAL SETUP



A Trans-Tek Incorporated Model 1003 Transducer with a Series 240 linear variable differential transformer (LVDT) was used for all testing; it was calibrated using Hoke Precision Gage Blocks. The 4.44 N force was applied with a standard mass machined from steel. The utensils were secured with a standard bench vise. The entire assembly was secured on a ~5 mm thick aluminum plate. To determine deflection consistency, the deflection on each of the 15 forks, 15 knives, and 15 spoons from each of the 13 bio-based and 6 petrochemical based utensils was measured.

Table 2 provides general information on the load locations for each utensil.

TABLE 2: GENERAL LOCATION OF APPLIED LOAD (4.44 N) LOCATION, AND ORIENTATION FOR EACH UTENSIL

Utensil	Location of vice	Location of deflection point	Utensil orientation (force down)
Fork	50.8 mm from base of tines	Base of tines	Tines point up
Knife	101.6 mm from tip of knife	12.7 mm from tip of knife	Cutting edge flat
Spoon	88.25 mm from widest section of spoon	Widest section of spoon	Bowl of spoon up

It is important to note that the tested deflection orientation for forks and spoons was the same orientation in which the utensil would be used by a consumer (see Figure 1). For knives, the load was applied as a sideways load and not as a cutting load.

During testing relative humidity (Rh) ranged between 30% and 50% and testing temperatures ranged between 20 ºC and 25 ºC, as defined by the CID standard.

BIO-BASED CONTENT MEASUREMENTS

To confirm the bio-based content, bio-based utensils were tested by Beta Analytic in Miami, Florida, following the ASTM D6866 standard. In general, the standard compares the carbon content of the product for fossilized carbon (only trace amounts of radioactive C14) and "organic" carbon (containing measurable C14).

FINITE ELEMENT ANALYSIS

Finite Element Analysis (FEA) models were constructed to compare the deflection of conventional and bio-based utensils using a Solidworks FEA solver. A model of the utensils was generated by scanning actual utensils with a three-dimensional scanning system to generate files that were imported into Solidworks. The boundary conditions were zero degrees of freedom at the clamping locations, linear material properties, and a static load at the edge of the utensils corresponding to the location of the applied load.

Table 3 lists the mechanical properties of the selected resins that were used for the FEA models as reported by the resins' technical data sheets.

TABLE 3: MECHANICAL PROPERTIES OF MATERIALS ANALYZED (NOTE NON-SI UNITS)

Material	Density (g/cm^3)	Poisson's Ratio	Elastic Modulus (psi)	Yield Strength (psi)
500W Polystyrene	1.04	0.3	4.5×10^5	6,400
2003D Ingeo PLA	1.24	0.3	5.0×10^5	8,700

RESULTS

Bio-based Content

Table 4 shows that the bio-based content (in percent by weight) of the various utensils varied between 42 and 89% (wt.). It is important to note that in most bio-based utensils the bio-based content ranged between 45 and 53%, while one (G) had a relatively high bio-based content (89%). Because the bio-based content for cutlery from Company G was so high compared to the other 12 companies, its cutlery was not used in the statistical models developed later in this paper. It was assumed that additives, such as heat stabilizers and plasticizers, as well as petrochemical plastic materials made up the balance of the bio-based materials. This assumption could not be proven because utensil manufacturers would not disclose their chemical formulas nor would they allow compositional testing, as they wanted to ensure the proprietary nature of their products.

TABLE 4: RESIN TYPE AND RELATIVE BIOBASED CONTENT

Company	Resin Type	Bio-based Content (%) wt.	Company	Resin Type	Bio-based Content (%) wt.
A	Biobased	53	K	Biobased	52
B	Biobased	45	L	Biobased	47
C	Biobased	46	M	Conventional	Not applicable [a]
D	Biobased	52	N	Conventional	Not applicable [a]
E	Biobased	54	O	Biobased	50
F	Biobased	48	P	Conventional	Not applicable [a]
G	Biobased	89	Q	Conventional	Not applicable [a]
H	Biobased	49	R	Biobased	53
I	Biobased	45	S	Conventional	Not applicable [a]
J	Conventional	Not applicable [a]			

[a] Not applicable because utensils were not made from bio-based resin

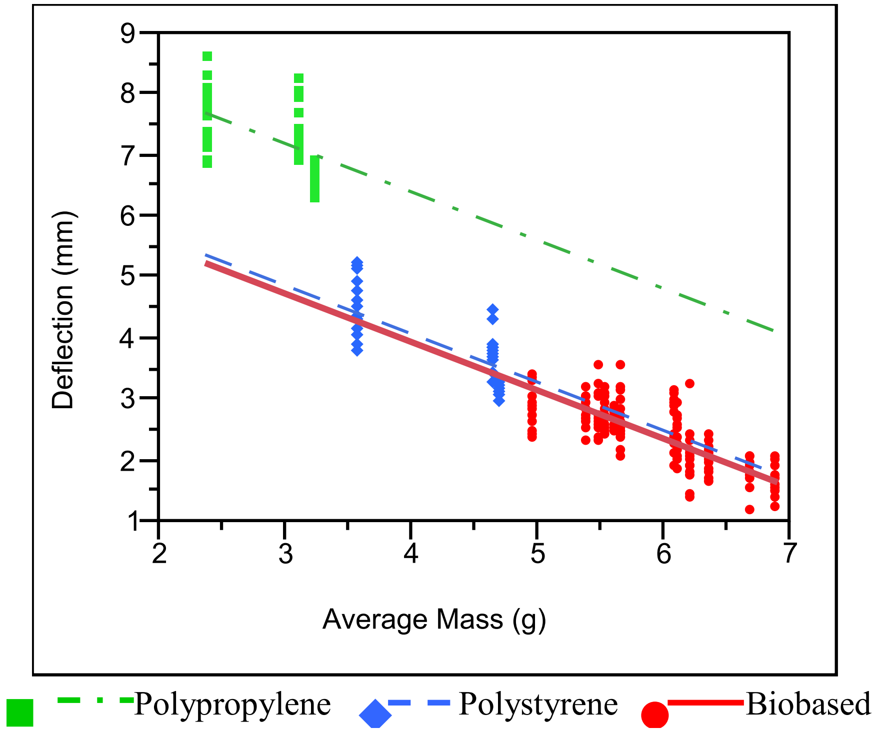
DEFLECTION RESULTS

FORKS

All bio-based forks met the flexibility standard set by the CID, as did all conventional forks. Bio-based forks also exhibited a relatively low level of deflection compared to the petroleum-based plastic forks tested.

Multiple linear regression was used to statistically determine if a utensil's mass was related to the measured level of deflection. A linear model was used because of the apparent straight line relationship between mass and deflection, as seen on the plot in Figure 2. Forks from Company G (bio-based content 89% (wt.)) were excluded from the analysis because their high bio-based content was an outlier compared to the other utensils.

FIGURE 2: REGRESSION OF DEFLECTION (mm) ON AVERAGE MASS (g) FOR FORKS FROM ALL THREE RESIN TYPES



The overall fit of the model was relatively good, with an R^2 value of 0.959 indicating that approximately 96% of the variation in utensil deflection can be explained by the linear relationship between deflection and mass for the three resin types. To determine this value, all three resin types were analyzed and their respective values are represented in Figure 2 by three separate lines. The prediction equations for these three lines are given Equations 1-3.

Bio-based:	Predicted deflection = 7.101 – 0.7923×Average Mass (g)	(1)
Polystyrene:	Predicted deflection = 7.235 – 0.7923×Average Mass (g)	(2)
Polypropylene:	Predicted deflection = 9.562 – 0.7923×Average Mass (g)	(3)

As seen in Table 5 and the values of the Prob> |*t*| the difference between polypropylene and both polystyrene and the bio-based resins was statistically significant (low Prob> |*t*| value), while there was no statistically significant difference between polystyrene and the bio-based resins with respect to the relationship between mass and deflection.

TABLE 5: COMPARISON OF VARIOUS MATERIALS AND DEFLECTION (FORK)

Summary of Fit

r^2	0.959
r^2	0.958
Root Mean Square Error	0.382
Mean of Response	3.450
Observations (or Sum Weights)	270

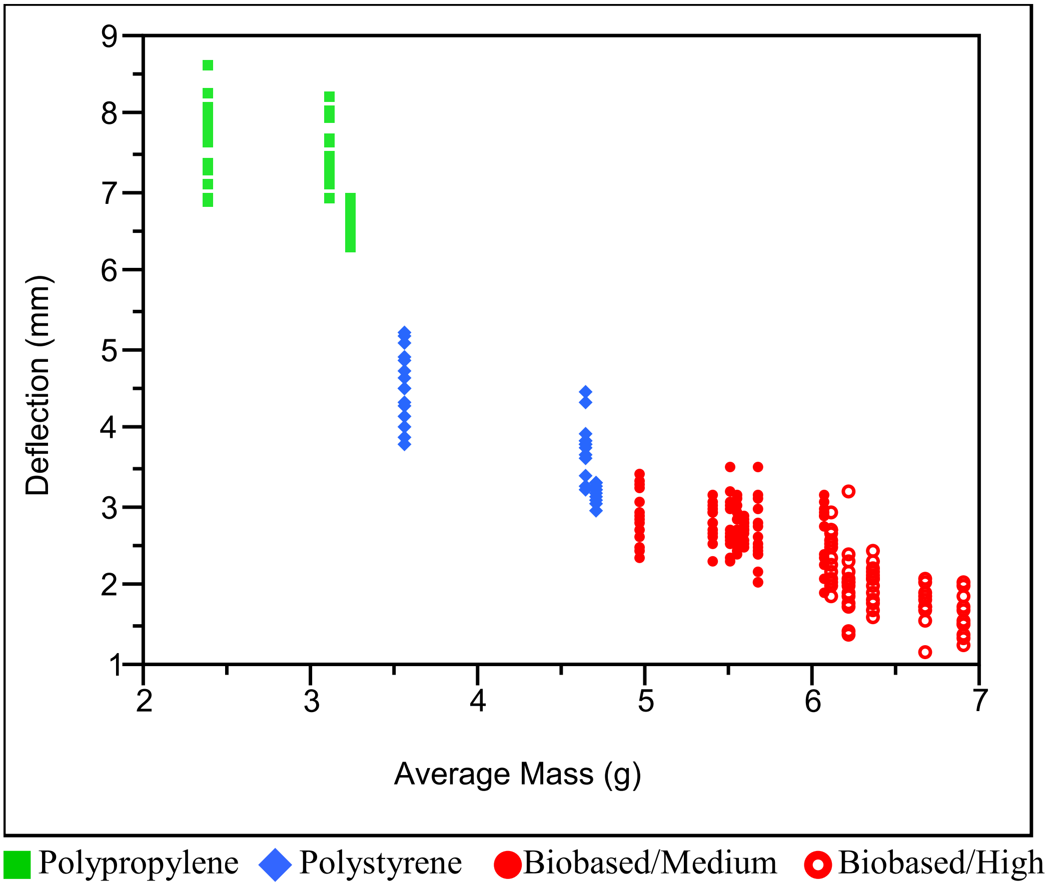
Comparison between Resins

Comparison	Difference	Std Error	t Ratio	Prob > |t|
Polypropylene vs Polystyrene (conv.)	2.327	0.1024	22.73	<.0001*
Polypropylene vs Bio-based Material	2.461	0.1505	16.35	<.0001*
Polystyrene vs Bio-based Material	0.134	0.0970	1.38	0.1676

Figure 3 shows deflection as a function of mass and the relative number of ribs incorporated in the utensil design for the various resins. The utensils are classified into three categories, a) no ribs, b) medium number of ribs, and c) high number of ribs. In more detail, if the utensil had one rib on the outside profile (outside) of the fork and one rib down the center of the fork handle, it was listed in the medium number of ribs category. In order to be classified as a utensil with a high number of ribs, the forks had to contain both a rib around the profile (outside) of the fork and in the back of each fork tine. The height or width of the rib was assumed inconsequential.

FIGURE 3: FORK DEFLECTION AS A FUNCTION OF UTENSIL MASS AND NUMBER OF RIBS

(polypropylene and polystyrene = no ribs, biobased/medium = 2-3 ribs, biobased/high >3 ribs)



As can be seen in Figure 3, the deflection was inversely proportional to fork mass and the number of ribs incorporated in the design. This was expected, as stiffness increases with cross-sectional area, which is proportional to the mass. The moment of inertia also increases with rib stiffeners. It is important to note that the polypropylene and polystyrene utensils were designed without ribs, while the bio-based utensils were designed with a high number of ribs.

In other statistical analysis it was found that the % bio-based content did not have any significant to the deflection. However, the number of ribs in bio-based forks did have a significant effect on the respective utensil's deflection. The two prediction equations for medium and high numbers of ribs are Equations 4 and 5.

Medium number of ribs: Predicted deflection (mm) = 5.423 – 0.486×Average Mass (g) (4)

High number of ribs: Predicted deflection (mm) = 5.089 – 0.486×Average Mass (g) (5)

KNIVES

Only four of the bio-based knives exhibited deflection values below the CID standard of 38.1 mm. Knives from Companies H and L had average deflection below the CID standard of 38.1 mm but approximately one third of the knives tested had individual deflections above the CID standard. Knives from Company I had an average defection slightly above the CID standard but over half the knives had individual deflections above the CID standard. The remaining five bio-based knives and the six petroleum based knives had deflection values above the CID standard of 38.1 mm. Thus, many of the knives tested, independent of base material, failed the CID standard.

Multiple linear regression was used to examine the relationship between mass and deflection of the knives for each of the resin types. Knives from Company G (bio-based content 89% (wt.)) were excluded from the analysis because their high bio-based content made them outliers. As seen in Table 6 and Equations 6 and 7, the correlation between average mass and deflection is seen. It is important to note that was no linear relationship between mass and deflection for polystyrene knives ($R^2 = 0.097$) and thus they were excluded. In addition, there was no statistically significant difference between polypropylene and bio-based knives in terms of the relationship between mass and deflection (high Prob> $|t|$ value).

Predicted deflection (Bio-based) = 122.30 – 15.33×Average Mass (g) (6)

Predicted deflection (Polypropylene) = 131.89 – 17.46×Average Mass (g) (7)

TABLE 6: DIFFERENCES BETWEEN BIO-BASED AND POLYPROPYLENE KNIVES

Difference in	Difference	Std Error	t Ratio	Prob > |t|
Intercepts	131.89 – 122.30 = 9.59	8.8871	1.08	0.2815
Slopes	–17.46 – (–15.33) = –2.13	2.7466	–0.77	0.4392

Thus, a simple linear model predicting deflection as a function of average mass (g) was chosen as the best model for knives. With this model, 89% of the variation in deflection was explained by the linear relationship with average mass. The prediction equation based on this model is given Equation 8 and is shown in Figure 4.

Predicted deflection = 123.49 – 15.56×Average Mass (g) (8)

FIGURE 4: SIMPLE LINEAR REGRESSION OF KNIFE DEFLECTION (mm) WITH RESPECT TO AVERAGE MASS (g) for all 3 resin types

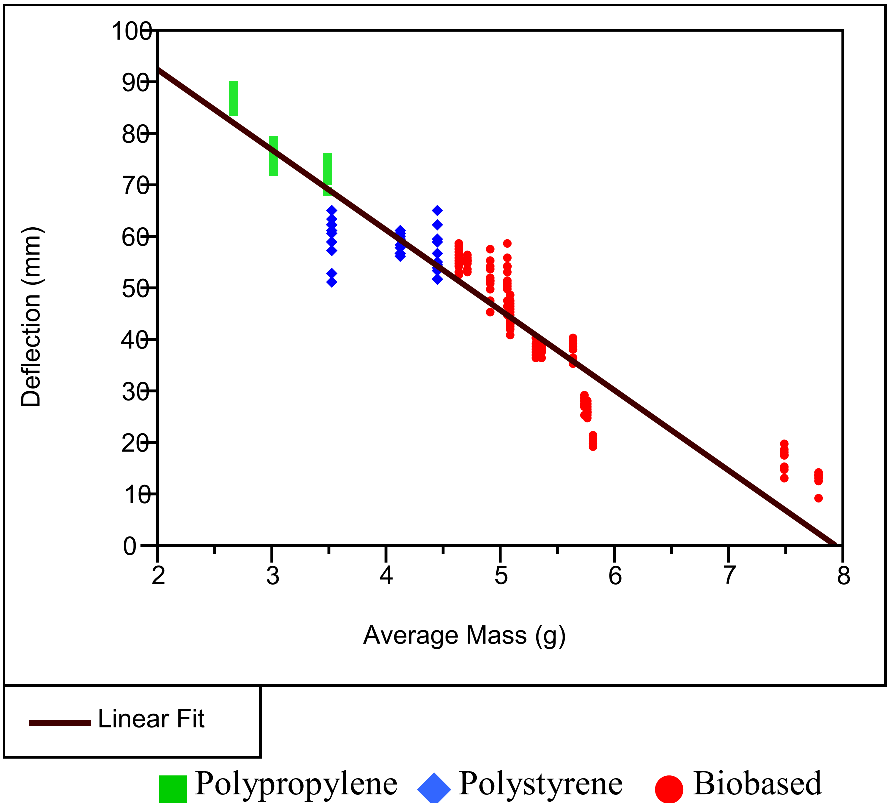


Figure 5 shows deflection as a function of mass and the relative number of ribs incorporated in the utensil design for the various resins. The same categories (None, Medium and High) as for the forks were used here.

FIGURE 5: KNIFE DEFLECTION AS A FUNCTION OF UTENSIL MASS AND THE NUMBER OF RIBS

(polypropylene and polystyrene = no ribs, biobased/medium = 2-3 ribs, biobased/high >3 ribs)

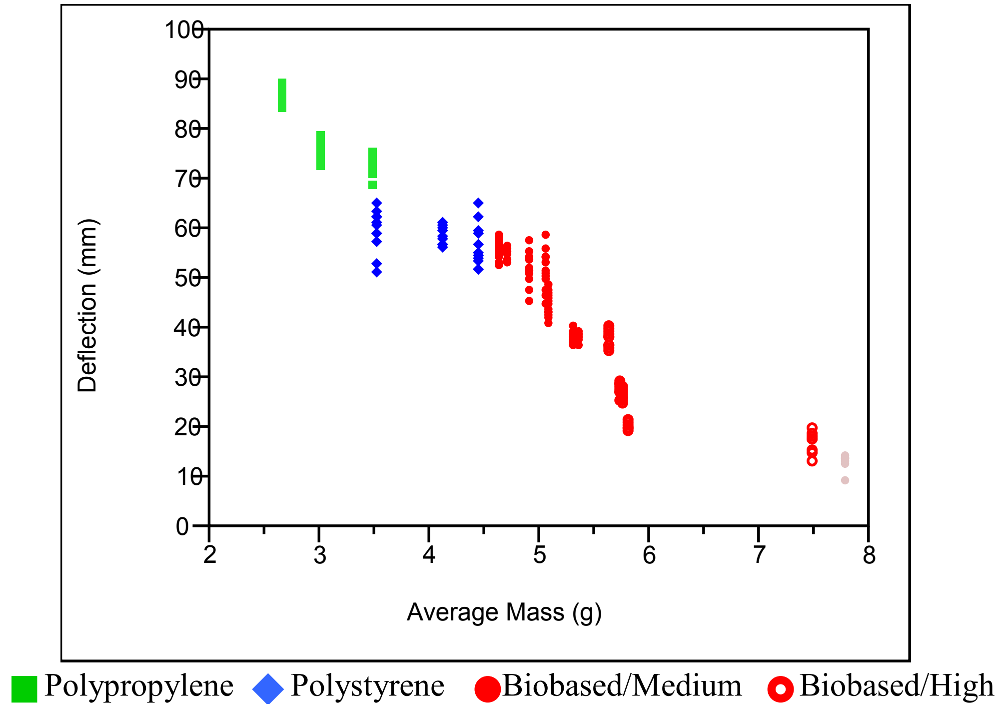


Figure 5 shows that the deflection was inversely proportional to knife mass and to the number of ribs incorporated in the design.

In order to compare only the bio-based knives, the relative effect of the percent of bio-based content and number of ribs was assessed. Unlike the results seen for forks, the percentage of bio-based content was a statistically significant predictor of deflection for knives, even when average mass was considered as seen in Table 7. The multiple regression prediction equation explained 92% of the variation in deflection using both average mass and percentage of bio-based content, see Equation 9.

Predicted deflection (mm) = 218.48 – 3.42×Average Mass (g) – 3.26×% Bio-based Content (9)

TABLE 7: COMPARISON OF DEFLECTION WITH VARYING BIOBASED CONTENT FOR KNIVES

Summary of Fit

r^2	0.918
r^2	0.918
Root Mean Square Error	3.736
Mean of Response	38.361
Observations (or Sum Weights)	180

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob > |t|
Intercept	218.48	5.2955	41.26	<.0001*
Average Mass (g)	–3.42	0.7129	–4.80	<.0001*
% bio-based content	–3.26	0.1646	–19.81	<.0001*

Once mass and percentage of bio-based content were included in the multiple regression model, the number of ribs did not have a statistically significant effect on deflection.

SPOONS

All bio-based spoons had deflection values below the standard of 25.4 mm set by the CID, while only two of the six petrochemical spoons met the specifications. The deflection values for spoons produced by Company M were unusually high (63 to 66 mm with an average of 64.6 mm). Consistent with the previous analyses, spoons from Company G (89% bio-based content) were excluded when the relationship between mass and deflection was investigated.

Multiple linear regression was used to model the relationship between average mass (g) and the deflection (mm) for the three material types. The analysis indicated that the three resin types differed significantly from each other, see Equations 10-12 (Regression in Table 8) and Figure 6.

Biobased: Predicted deflection (mm) = 40.31 – 4.56×Average Mass (g) (10)

Polypropylene: Predicted deflection (mm) = 116.10 – 28.44×Average Mass (g) (11)

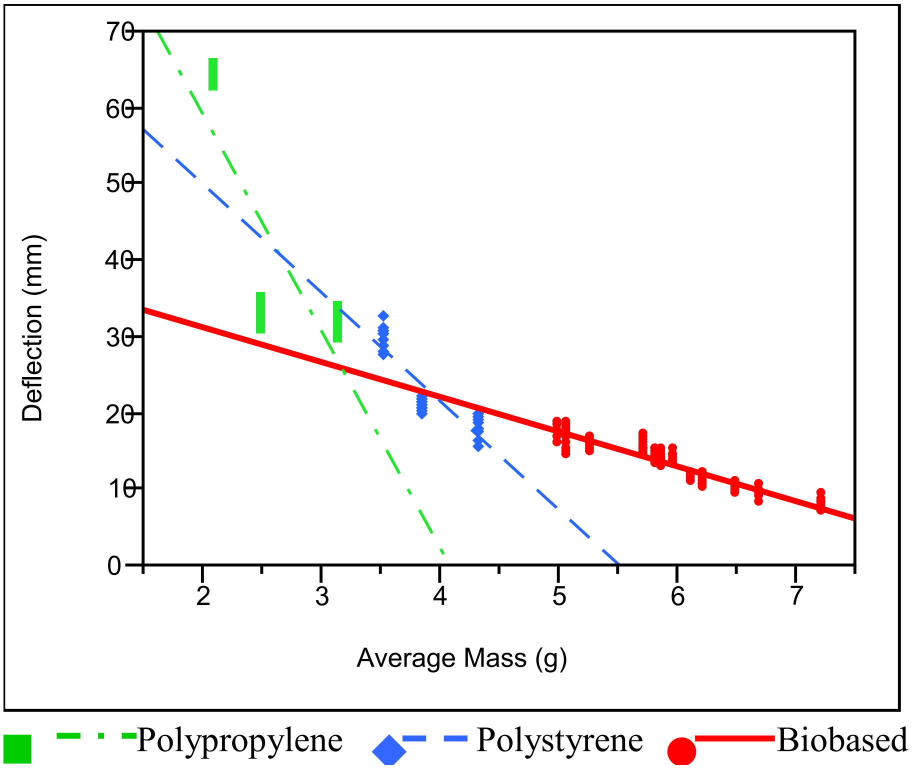
Polystyrene: Predicted deflection (mm) = 78.48 – 14.24×Average Mass (g) (12)

TABLE 8: DIFFERENCES IN INTERCEPTS AND SLOPES FOR SPOONS

Intercepts	Difference	Std Error	t Ratio	Prob > |t|
Polypropylene vs Biobased	75.79	4.4171	17.16	<.0001*
Polystyrene vs Biobased	38.17	7.4555	5.12	<.0001*
Polypropylene vs Polystyrene	37.62	7.7515	4.85	<.0001*

Slopes	Difference	Std Error	t Ratio	Prob > |t|
Polypropylene vs Biobased	–23.88	1.4088	–16.95	<.0001*
Polystyrene vs Biobased	–9.68	1.8294	–5.29	<.0001*
Polypropylene vs Polystyrene	–14.20	2.2166	–6.41	<.0001*

FIGURE 6: REGRESSION OF DEFLECTION (mm) ON AVERAGE MASS (g) FOR SPOONS FROM ALL 3 RESIN TYPES



The overall fits of three models was relatively good, with R^2 values of 0.892, 0.659, and 0.799 for bio-based, polypropylene and polystyrene, respectively.

Figure 7 shows deflection as a function of mass and the relative number of ribs incorporated in the utensil design for the various resins.

FIGURE 7: SPOON DEFLECTION AS A FUNCTION OF UTENSIL MASS AND THE NUMBER OF RIBS

(polypropylene and polystyrene = no ribs, biobased/medium = 2-3 ribs, biobased/high >3 ribs).

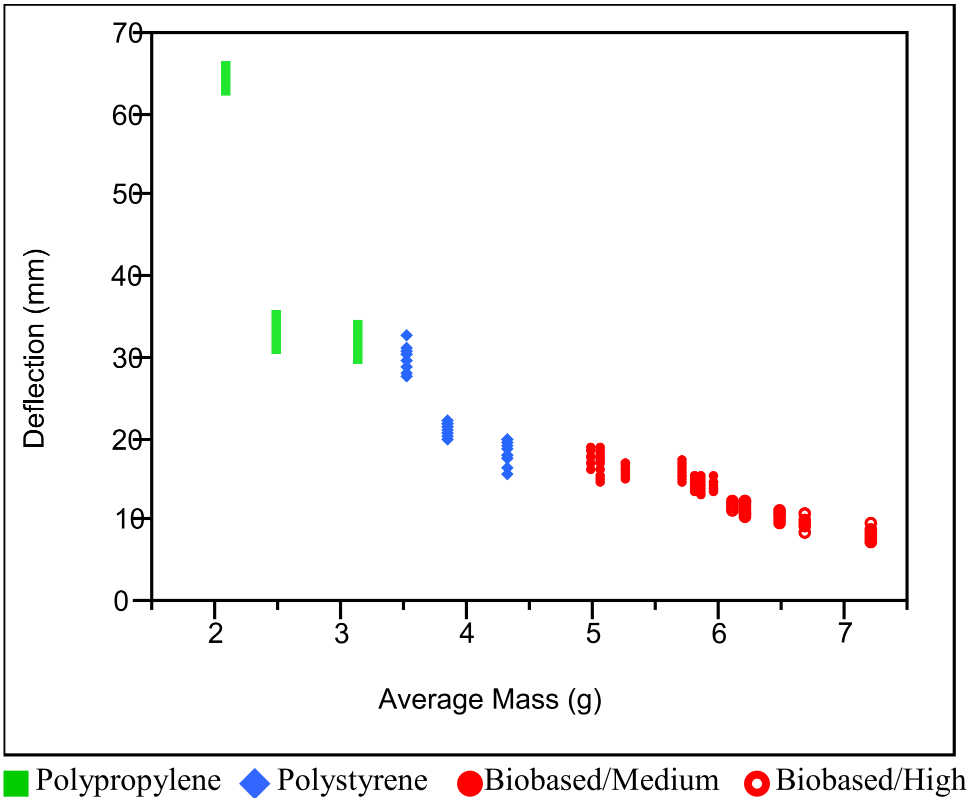


Figure 7 shows that the deflection was inversely proportional to spoon mass and the number of ribs incorporated in the design. This was expected, as detailed earlier for the tests with forks and knives.

Of the bio-based spoons, those with a high number of ribs tended to have the higher percentage of bio-based content. Therefore, adding either, but not both, bio-based content or number of ribs to the model with average mass provides a better prediction of deflection. Two competing models are given Equations 13-15.

Model with average mass (g) and % bio-based content:

Predicted deflection = 51.125 – 2.128×Average Mass (g) – 0.511×% Bio-based Content (13)

$R^2 = 0.916$

Model with average mass (g) and number of ribs:

Medium number of ribs: Predicted deflection = 33.609 – 3.294×Average Mass (g) (14)

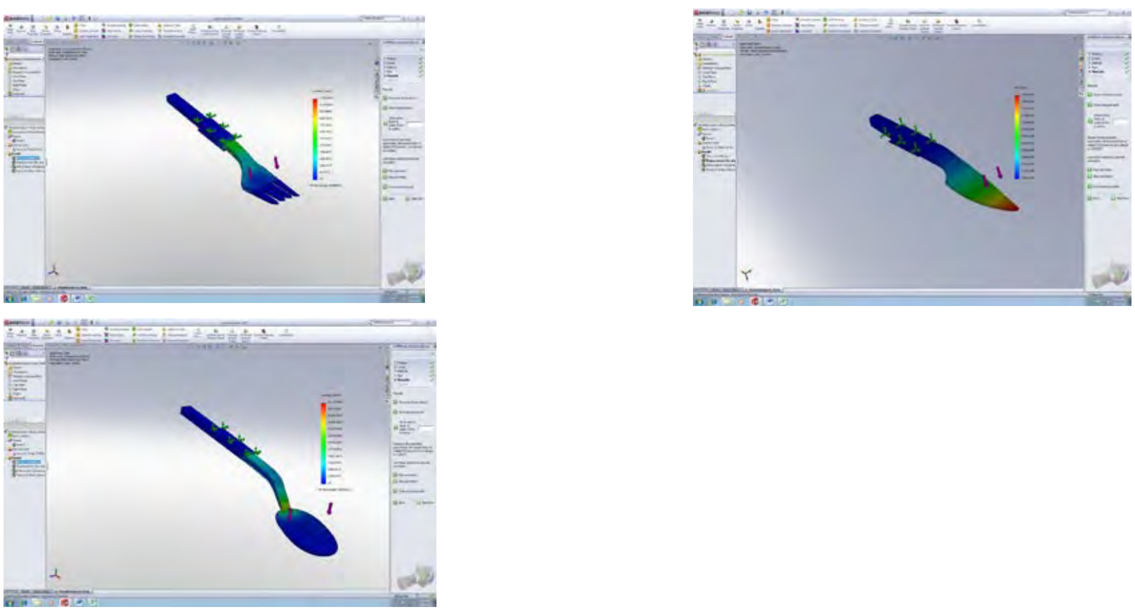
High number of ribs: Predicted deflection = 31.577 – 3.294×Average Mass (g) (15)

The dominant independent variable was the number of ribs, which was generally proportional to the bio-based content. While there was no conclusive evidence, this suggests that manufacturers assume that bio-based materials require additional ribs to protect against excessive deflection.

FEA RESULTS

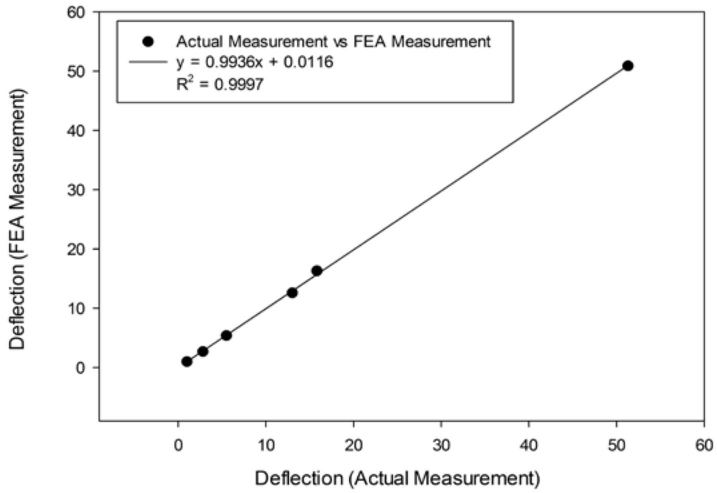
Finite element analysis results showed that the highest concentrations of stress occurred in the handle of the utensil for the forks and knives, while spoons also experienced high levels of stress where the handle joined the spoon bowl.

FIGURE 8: DETAILS OF DISPLACEMENT FEA MODELS



The models were validated with experimental data as detailed in Figure 9 for three biobased and three petrochemical products at various loads to assure a wide range of deflection. There was relatively good agreement between the experimental (measured) and predicted values as the slope of the line is nearly 1.0 (0.9936), with an $R^2 > 0.99$.

FIGURE 9: CALCULATED AND EXPERIMENTAL (measured) DEFLECTION FOR VARIOUS PRODUCTS



CONCLUSIONS

In general, the bio-based utensils performed better compared to the conventional utensils in terms of deflection. Overall, 76% of the bio-based utensils (30 of the 39 spoons, knives, and forks) met the CID specifications, while only 44% of the conventional utensils met the CID specifications. In more detail, all bio-based spoons met CID specifications, while four conventional spoons did not. All bio-based and petrochemical forks met the CID specifications. In more detail, four of the thirteen bio-based knives met the CID specifications for all 15 specimens tested with two additional bio-based knives exhibiting an average value below 38.1 mm. None of the conventional knives met the CID specifications.

Testing and statistical analysis showed that bio-based plastic and conventional polystyrene utensils exhibited similar properties, while the polypropylene utensils exhibited different properties. Statistical data indicate that with increases in mass and the addition of rib stiffeners in the design, the overall amount of deflection for forks, spoons, and knives decreases.

The deflection of the utensils could be predicted using standard FEA models and standard material properties.

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