

2011

Comparison and analysis of biobased/ biodegradable and petrochemical cutlery flexibility

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Comparison and analysis of biobased/biodegradable and petrochemical cutlery flexibility

by

Brian John Demmer

A thesis submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of
MASTER OF SCIENCE

Major: Industrial & Agricultural Technology

Program of Study Committee:

David Grewell, Major Professor

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Ames, Iowa

2011

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DEDICATION

This paper is dedicated to my loving family and friends

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ACKNOWLEDGMENTS

I want to thank the Iowa State University Center for Industrial Research and Service (CIRAS), along with Steve Devlin, Jessica Riedl, and John Roberts for helping me throughout my research.

I also want to thank my committee members, Dr. Steve Freeman and Dr. Carolyn Heising, for agreeing to be a part of my committee and guiding me in my research.

Special thanks to my major professor, Dr. David Grewell, for his guidance and support throughout my work.

ABSTRACT

Biorenewable plastics are a potential solution to the growing problems of pollution caused by petroleum-based plastics, overcrowded landfills and America's dependency on foreign petroleum. This study compares thirteen biobased/biorenewable cutlery brands with six petrochemical cutlery companies in terms of weight, stiffness, maximum load at failure, and specific stiffness (stiffness/weight). The Commercial Item Description (CID), which was created by the General Services Administration (GSA) within the U.S. Government, is the standard that defines the basic governmental specifications for biobased cutlery. The CID specification details that the utensils can have any percentage of biobased content and maximum deflection under certain loads. A biobased product for this study is defined by the GSA as “a product determined by USDA to be a commercial or industrial product (other than food or feed) that is composed, in whole or in significant part, of biological products or renewable domestic agricultural materials (including plant, animal, and marine materials) or forestry materials.” The results of this study show that several biobased products performed similar to or better than petrochemical products, while still meeting the CID specifications.

CHAPTER 1. INTRODUCTION

1.1 Introduction

During the past few decades, plastics have become a vital part of our lives. Few aspects of our daily lives are not touched by the use of plastic. Everyday items, such as grocery/trash bags, shampoo bottles, computers, cellular telephones, automobile body panels, and food packaging, are all manufactured from plastics.

In addition to the wide variety of products already made from plastic, designers and engineers continue to use plastic because of its ease of manufacture, flexibility, and wide range of properties and costs. This has helped propel the plastic industry into one of the largest in the world. Between 1950 and 2008, plastic production worldwide has risen dramatically from 5 million tons per year to just under 250 million tons, as shown in Figure 1 [33].

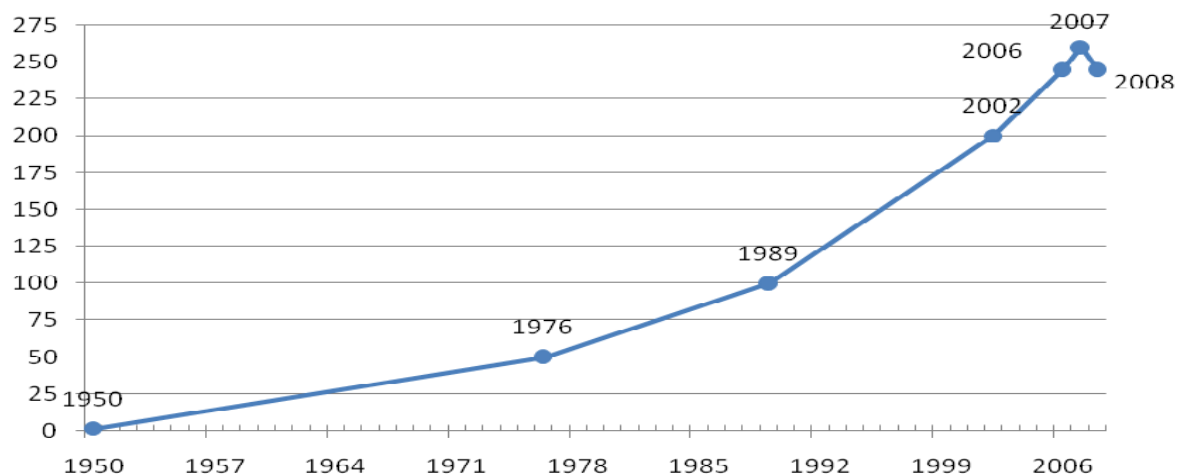


Figure 1. World plastics production 1950–2008 for thermoplastics, polyurethanes, thermosets, elastomers, adhesives, coatings and sealants, and PP-fibers [33].

The plastics industry is currently the third largest manufacturing industry in the United States, employing more than 1.1 million workers and grossing \$374 billion in annual sales [44]. As of 2007, the United States had more than 17,600 plastics manufacturing facilities, including at least one in each state. Figure 2 shows approximately how many workers are employed in the plastics industry in each state and where the majority of the manufacturing occurs [44].

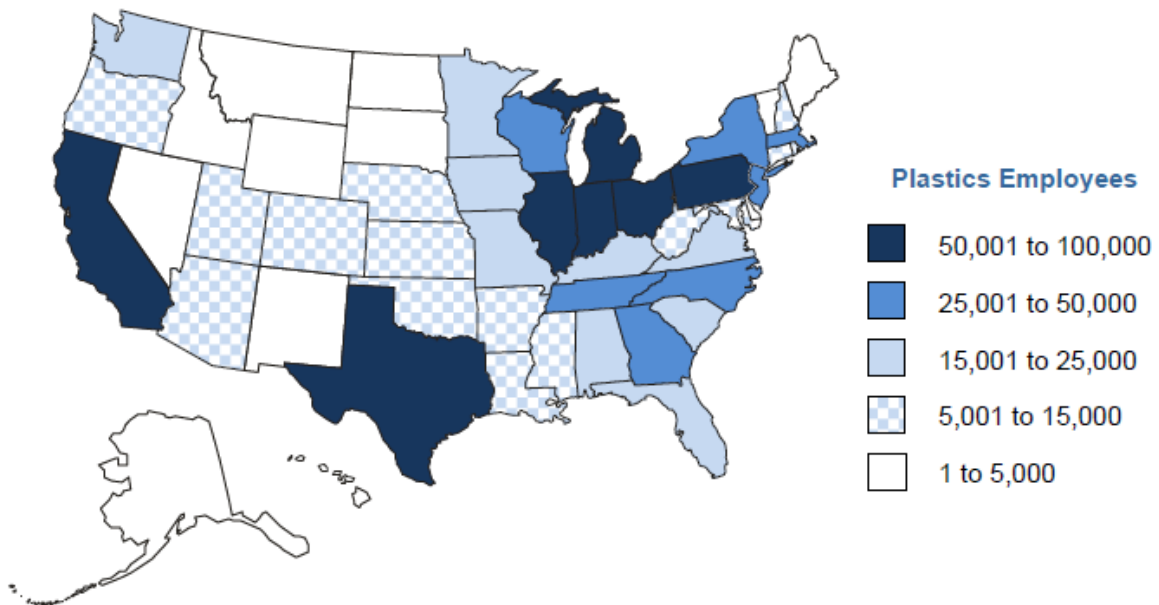


Figure 2. Location of plastics manufacturers and numbers of industry employees in the United States [44].

The U.S plastics industry generated a “\$10.9 billion trade surplus during 2007 and has grown 3.1% per year since 1980. Over the past 27 years, productivity in plastic manufacturing plants has grown 2.2% per year, which is faster than the productivity growth for manufacturing as a whole” [47]. Recent research shows that the largest use of plastics in

the United States is in packaging (32%), including bags, food packaging, and bottles. The next largest market sectors, as shown in Figure 3, are consumer and institutional at 21%, followed by building and construction at 16%.

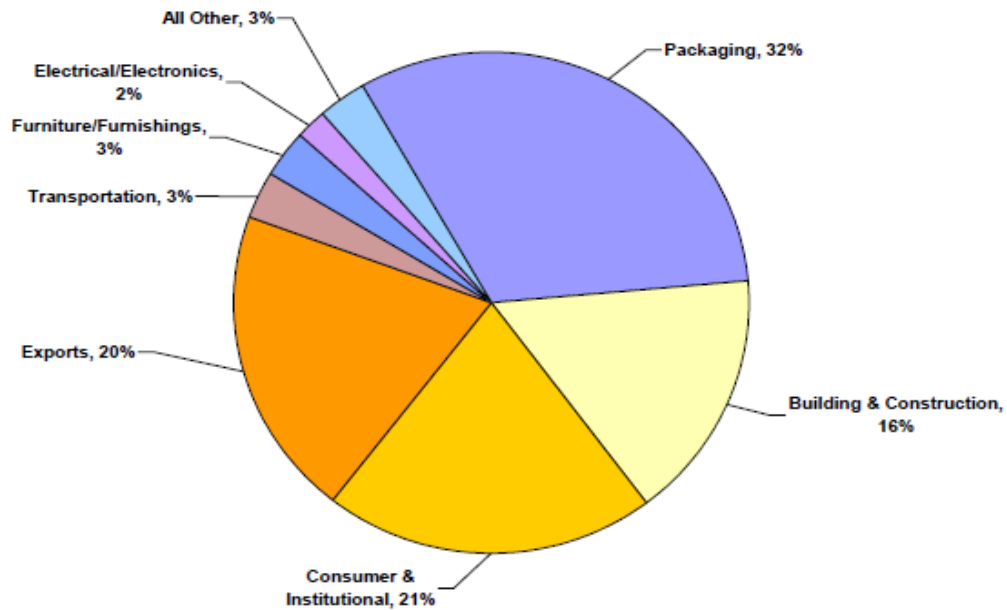


Figure 3. 2009 United States plastics usage by market [2].

The plastics industry manufactures 13 major resins, which are listed below [21]:

- Low Density Polyethylene (LDPE)
- High Density Polyethylene (HDPE)
- Acrylonitrile-Butadiene-Styrene (ABS)
- Polystyrene
- Styrene Butadiene Latexes (SBL)
- Nylon
- Polyurethanes
- Linear Low Density Polyethylene (LLDPE)
- Polypropylene (PP)
- Styrene-Acrylonitrile (SAN)
- Epoxy
- Thermoplastic Polyester
- Polyvinyl Chloride (PVC)

All of these resins are petroleum-based plastics, which represent 95% of total petroleum plastics consumption and, with the exception noted below, are neither renewable nor biodegradable [31, 34]. The exception is Brazil's production of polyethylene from sugarcane, which is the country's number one source of renewable energy. As of 2009, Brazil used close to seven million tons of plastics. Still, although Brazil makes a small percentage of plastic from sugarcane, the industry as a whole has an extreme dependence on oil. As of 2010, for example, the United States used 20.0 million barrels of oil per day, which is more than 25% of the world's total production [30]. Increased consumption of oil and plastics around the world is caused by three key factors: (a) population growth, (b) new uses found for plastics, and (c) an increase in living standards [34].

Even with crude oil prices reaching \$100 per barrel and despite predictions that the United States will exhaust its supply of oil in as little as 40 years, demand is rising and is expected to continue increasing because of the growing population. This concern has sparked many heated debates among American political parties and citizens addressing the issue of global warming. In particular, they ask, "How long can the United States depend upon foreign oil for sources of energy and ingredients to major materials such as plastic?" Further, a number of these overseas countries are in the midst of hostilities and international political disputes. As a result, the United States needs to consider alternative sustainable resources.

In addition, environmentalists have raised concerns about the substantial amount of pollution created by both the use of petroleum as an energy source and as a feedstock for plastics. Concerned groups have endorsed many studies to further investigate and understand global warming, the effects it has already had on the earth, and how future environmental

changes can be avoided [10]. Thus, there is a driving demand to find new biorenewable feedstocks for plastics. A highly anticipated alternative to petrochemicals is to make use of biorenewable resources that offer savings when compared to oil, coal, and natural gas. Biorenewable resources not only provide an alternative energy source that is abundant domestically, they give the United States the ability to reduce the carbon footprint from a variety of pollutants, such as particulate matter, sulfur, carbon dioxide, and carbon monoxide, that are continuously released into the atmosphere by burning fossil fuels [10]. Alternative resources would create a closed-loop system that would lower greenhouse gas emissions by circulating the carbon as shown in Figure 4.

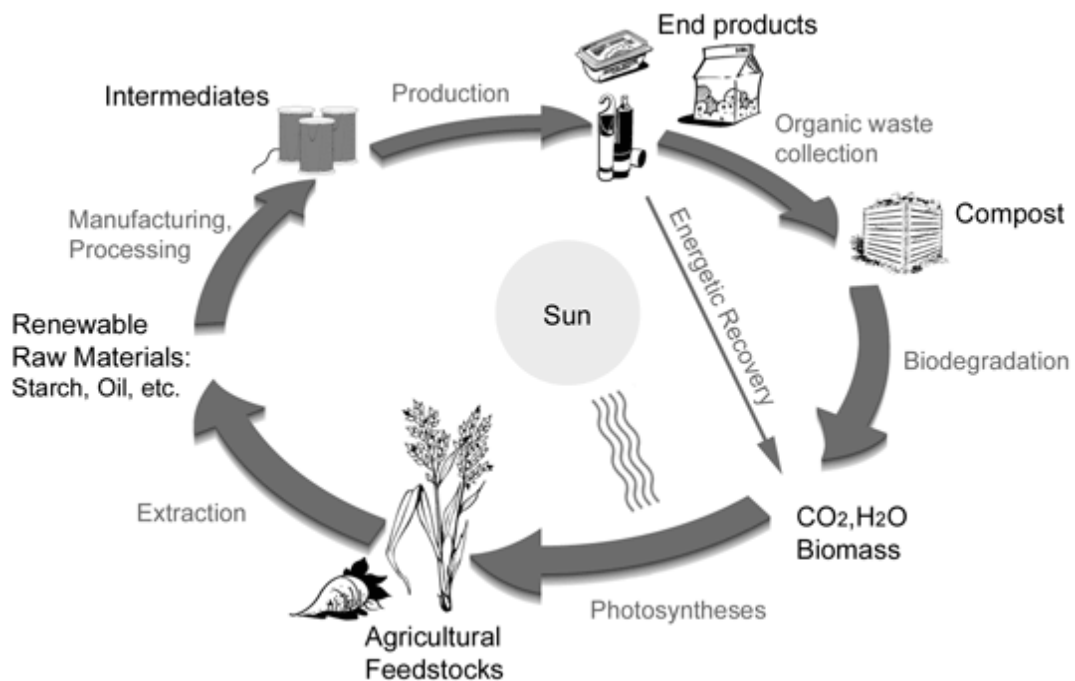


Figure 4. Closed cycle of bioplastics [18].

Many people in the United States are striving for this closed-loop carbon system. In addition to reduced emissions and dependence on foreign materials, renewable feedstocks help strengthen the nation's struggling economy by promoting agriculture and other related industries. Agriculture is critical to the American economy, as many other industries, such as manufacturing, depend on its success. For example, a successful agricultural economy promotes the purchase of capital equipment (tractors, combines, and other machinery), which helps keep American manufacturing facilities profitable.

1.2 Environmental Advantages of Biorenewable Polymers

The Farm Security and Rural Investment Act (FSRIA) defines a biobased product as “a commercial or industrial product (other than food or feed) that is composed in whole or in significant part of biological products including renewable domestic agricultural materials and forestry materials, or an intermediate ingredient or feedstock” [20].

Biorenewable resources are defined by Brown, a professor at Iowa State University, as “organic materials of recent biological origin” and “sustainable natural resources” [40]. It can be inferred from both definitions that biorenewable resources and biobased products are agricultural based. Agriculture, as previously mentioned, is one of the major components of the U.S. economy. These definitions suggest agriculture offers opportunities for creating alternative feedstocks for the plastics industry. The mass quantities of corn and soybeans produced in the United States and the fact that both are major cash crops make these opportunities more economically attractive than other alternatives, such as switch grass, algae, or sugarcane.

Bioplastics are made from dextrose (sugar) and glucose that is derived from field corn, which is already grown for many industrial and functional end uses. In North America, corn has been the most-used material because it is the most economically feasible source of plant starches. However, bioplastics do not require corn; they only require a sugar source. Starches potentially can be derived from sugar beets, sugar cane, and wheat. Bioplastic production would require less than 1/20th of 1% (0.0005%) of the annual global corn crop today, so there would be little to no impact on food prices or supply [50]. In short, bioplastics will not replace all traditional plastics, but they are an alternative material source. Current production practices price bioplastics higher than traditional plastic. Several years from now when the production price has been equalized, bioplastic could replace traditional plastics [50]. Figure 5 shows that less than five million tons of bioplastics are consumed today. Due to the manufacturing facilities and feedstocks available in the United States, bioplastics consumption is expected to rise to nearly 900 million tons by 2060 [6].

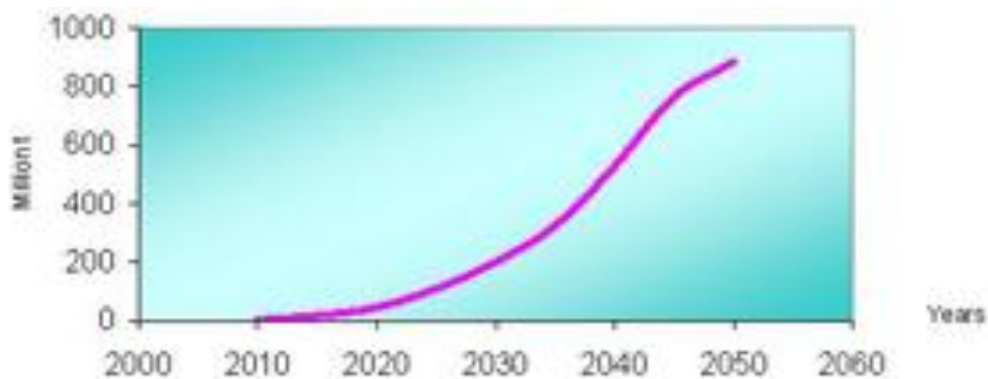


Figure 5. Amount of bioplastics consumed per year from 2000 to 2060 [6].

As stated, a major disadvantage of petroleum-based plastics is the generation of pollution. This has prompted the United States to push for the collection of biomaterials for new sources of energy, along with different feedstocks for many manufacturing materials, including plastics [50]. Natureworks LLC., a major resin manufacturer, stated that bioplastics production produces “60% less greenhouse gases than the manufacture of traditional polymers, while 50% less nonrenewable energy is used during the manufacturing process compared to traditional polymers such as polyethylene terephthalate (PET) and polystyrene (PS)” (see Figures 6 and 7) [50]. Measuring these two impacts and comparing the data between bioplastic and traditional polymers, such as PET and PS, help picture the eco-advantage provided by bioplastics [50]. The resin known as polylactic acid (PLA)—a bio-plastic used to form containers and packaging for food and consumer goods—has many advantages.

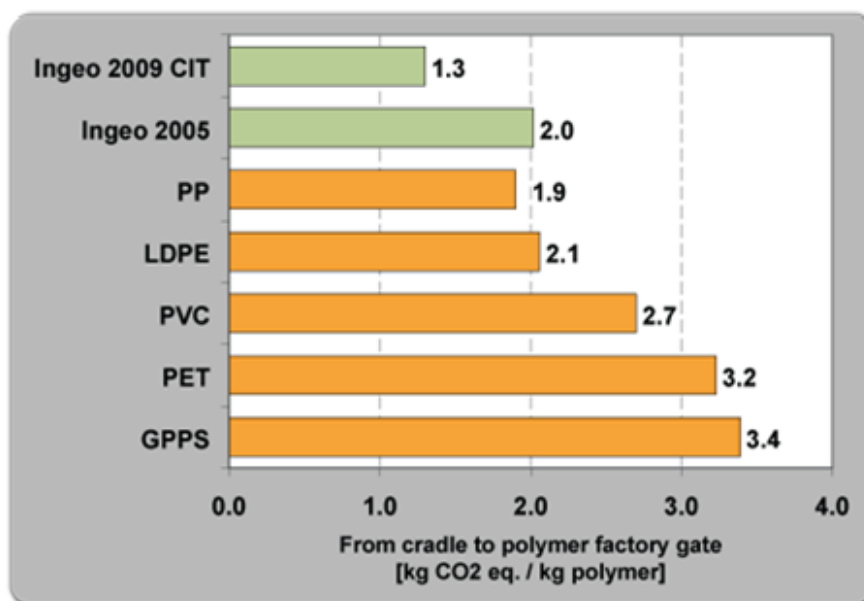


Figure 6. Comparison of greenhouse gas emissions from plastics manufacturing [50].

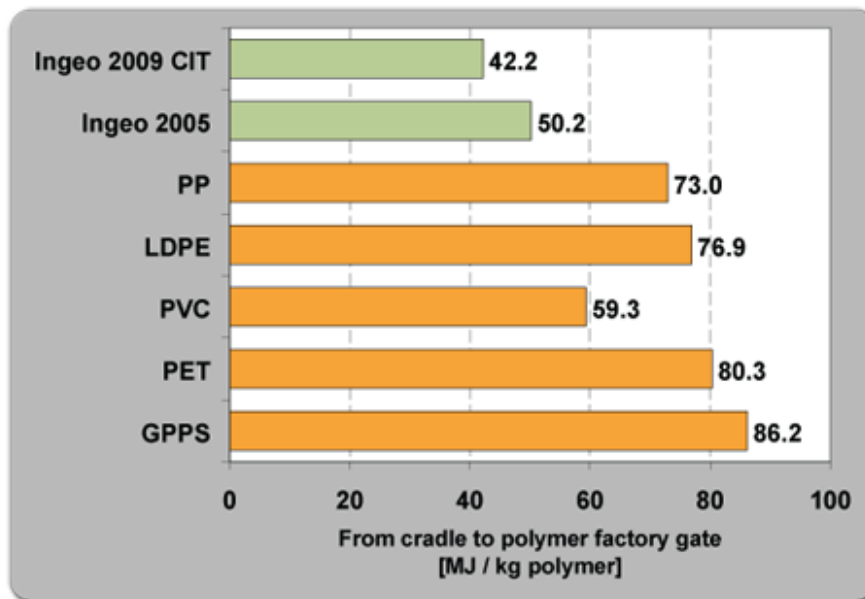


Figure 7. Comparison of nonrenewable energy use from plastics manufacturing [50].

Made from a renewable resource, it has a major environmental advantage over conventional plastic packaging, which uses an estimated 200,000 barrels of oil a day in the United States [43].

According to Elizabeth Royle, “if Wal-Mart used 114 million PLA food containers a year, this would save 800,000 barrels of oil annually” [43]. PLA is, in principle, compostable, meaning it will break down under certain conditions into harmless natural compounds. That could reduce the growth of the nation’s landfills, as plastics currently represent up to 25% of landfills by volume [14]. In addition, the manufacture of corn-based plastics is beginning to look more affordable, now that oil prices are so high [50].

Over the past several years, the United States has run into issues with a lack of sufficient landfill space, along with contamination of drinking water from drainage off of landfills [14]. Data from the Environmental Protection Agency (EPA) indicated that plastics

contributed up to 12%, or 30 million tons, of the total Municipal Solid Waste (MSW) generated in the United States in 2008, of which approximately 5.4% is recovered, as detailed in Table 1 [14].

The remainder of the material not recovered or recycled is thrown into landfills, incinerated, or dumped in the ocean, thereby causing pollution. Combustion of petroleum plastics produces greenhouse gases, while also emitting harmful toxins, such as dioxins, into the environment [14]. While recycling has increased over the past several years, as seen in Table 1 the amount of recycling of plastic remains relatively insignificant [14].

Table 1. *Generation and Recovery of Materials in MSW 2008 (in Millions of Tons and Percentage of Generation)* [14].

Material	Weight Generated	Weight Recovered	Recovery as Percent of Generation
Paper and paperboard	77.42	42.94	55.5%
Glass	12.15	2.81	23.1%
Metals			
Steel	15.68	5.29	33.7%
Aluminum	3.41	0.72	21.1%
Other nonferrous metals†	1.76	1.21	68.8%
Total metals	20.85	7.22	34.6%
Plastics	30.05	2.12	7.1%
Rubber and leather	7.41	1.06	14.3%
Textiles	12.37	1.89	15.3%
Wood	16.39	1.58	9.6%
Other materials	4.50	1.15	25.6%
Total materials in products	181.14	60.77	33.5%
Other wastes			
Food, other‡	31.79	0.80	2.5%
Yard trimmings	32.90	21.30	64.7%
Miscellaneous inorganic wastes	3.78	Negligible	Negligible
Total other wastes	68.47	22.10	32.3%
Total municipal solid waste	249.61	82.87	33.2%

Increasing production of solid waste, especially by petroleum plastics, has raised concerns, as most of these plastics do not degrade. The majority stay undamaged in their dumpsites for several hundred years, creating a reserve of uncirculated carbon. According to the MSW shown in Figure 9, plastics are one of the largest components of waste entering landfills today. While this successfully removes the carbon from the “green” cycle, it is stored in a form that plants or crops cannot utilize as an energy source. Increasing use of biorenewable resources for plastics could potentially reduce this effect because many biorenewable plastics are rich in carbon and nitrogen and act as an energy source for bacteria which are important in breaking down (such as composting) waste [14].

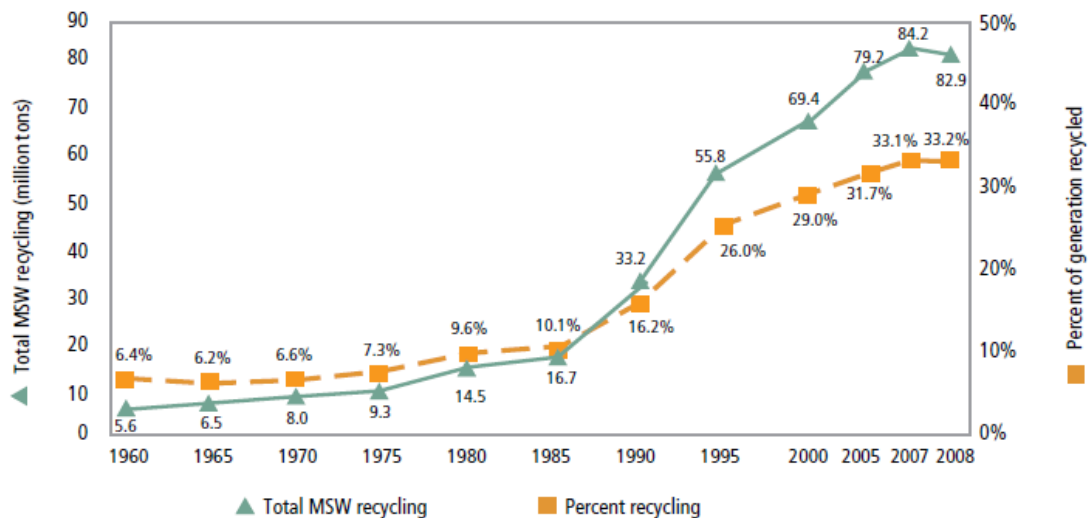


Figure 8. MSW recovery rates 1960–2008 [14].

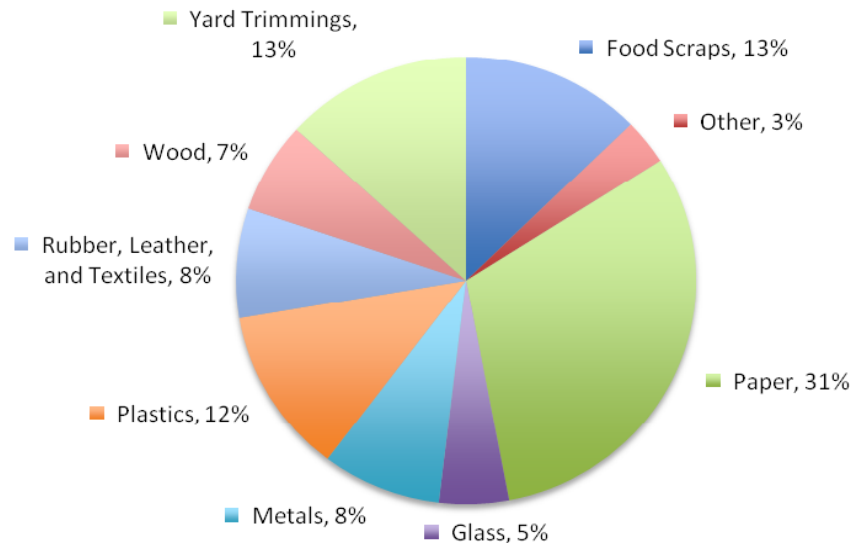


Figure 9. Total U.S. MSW generation by material in 2008, including waste from residential, commercial, and institutional sources [14].

1.3 History of Plastics

The word “plastic” is derived from the Greek word “plastikos,” which means the capability of being shaped or formed by heat [29]. Forming plastics by using heat is a basic part of nearly all plastic manufacturing processes. Thermoplastics can be heated and molded repeatedly; thermoset plastics use heat (energy) to initially take their molded shape, but they can only be formed once [3]. Thermoset plastics can also be spin cast using liquid resin which does not require heat. If reheated, thermoset material becomes brittle and breaks. Plastics are by definition polymers, which are a class of chemical structures that consist of long chains of repeating monomer units. Polymers can be further classified into natural and synthetic. One of the main distinctions between the categories is that natural polymers have existed in nature for millions of years, while synthetic polymers (plastics) have been a more

recent development. Humans have benefited from the use of natural polymers since approximately 1600 BC, when ancient Mesoamericans reportedly processed natural rubber into balls, figurines, and bands [3]. Natural polymers originated from animal bones, horns, tortoise shells, fossilized resin from pine trees known as amber, the sap from various tropical trees, and the wax from bees. For example, before the introduction of glass, transparent sheets from ox-horn were extensively used as windows [43].

During the early nineteenth and twentieth centuries, the invention of various materials enabled the creation of synthetic polymers. In 1839, Goodyear invented vulcanized rubber by purposely chemically modifying a natural polymer, known as rubber latex [9]. In 1862, the first manufactured plastic, known as Parkesine, was invented by an English metallurgist named Parkes [9]. He first demonstrated his discovery at the Great International Exhibition in London later that year, where he introduced molded combs, hair slides, billiard balls, and carved plaques. Parkesine was an organic material derived from cellulose that, once it was heated, could be molded and would retain its molded shape once cooled. Today Parkes is considered as one of the “fathers” of plastics [9]. Despite the early success of Parkesine at the International Exhibition and its flexibility in producing many kinds of domestic products, this cellulose product, sometimes referred to as cellulose nitrate because it could be dissolved in nitric acid, was still incredibly expensive and extremely flammable [55].

In 1968, replacing ivory in the manufacture of billiard balls resulted in the eventual business success of cellulose nitrate. However, it was soon discovered, that celluloid made from cellulose nitrate was explosive. Thus, when the billiard balls were knocked together, they sometimes exploded [55].

In the search for another substitute material for ivory, Hyatt and Hyatt first tried using collodion, but they discovered that if spilled, the material dried into a tough and flexible film that was not hard enough to transfer the energy of the impacts of a billiards game. They then produced a version of cellulose nitrate that was mixed with camphor. This allowed it to be molded with heat and pressure into a robust shape [4, 33]. The early commercial success of this type of celluloid resulted not only from its use in the manufacture of billiard balls, but also as the first flexible photographic film used for still photography and motion pictures. The Hyatt brothers eventually went on to create celluloid in a strip format for movie film. By 1900, movie film was an exploding market for celluloid [33].

At the beginning of the twentieth century, the flammability of cellulose nitrate prevented its use in high-temperature molding techniques. The quick development of cellulose acetate, however, resolved this issue [33]. Bakelite, the first truly synthetic polymer, was invented by Baekeland, and was patented in 1907 [33]. Baekeland was looking for a synthetic replacement for *shellac*, a black resin secreted by Asian beetles, which was used as electrical insulation, to seal out moisture, and to produce gramophone records until the advent of vinyl in the 1940s. Bakelite was first used as electrical insulation in cars and other industrial products. Due to its ease of manufacture and its relatively low price, it later found its way into consumer products, such as telephones and ashtrays. Early Bakelite products were mixed with wood dust to strengthen the material because of its brittleness, which explains why early Bakelite products are frequently brown in color [33].

Regardless of the origins of the developments of plastic materials during the early twentieth century, the growth of the polymer industry was hindered by a substantial lack in the understanding of polymers. In 1901, Fischer was the first to discover that natural

polymers were linked chains of molecules (monomers) [35]. Until the early 1920s, however, the common belief was that polymers consisted of physically associated aggregates of small molecules. In 1922, chemist Staudinger proposed a new theory that polymer chains were far longer than originally thought and were composed of giant molecules containing more than a thousand atoms linked together by covalent bonds. He was the first to use the term *macromolecules*. Only a few scientists, however, were in agreement with his viewpoint [35, 55].

Following the invention of Bakelite, numerous other types of plastics were successfully developed (e.g. PVC [polyvinyl chloride] in 1912 and cellophane in 1913). The period between World War I and World War II is regularly referred to as the “poly era” because some of the most important plastics were invented throughout those years. During that period, plastics became a prevalent material in the manufacturing of domestic products.

In the 1920s, plastic radios and telephones were created, and in the 1930s, mass production of plastic items were initiated, mainly because manufacturers developed technologies to produce plastics from petroleum (e.g. polystyrene, PVC [polyvinyl chloride], and acrylic polymers). One such technology was injection molding, which can be completely automated, thereby enabling mass production of products. These changes reduced part prices and put plastics within reach for everyone. In addition, in the 1930s, the most common types of plastics found today—nylon, and polyethylene—were produced [17].

World War II turned plastics into one of the most important military materials, as manufacturing switched from domestic products to wartime goods. Its development was highly secret, and plastics were essential for the development of aircraft canopies and smaller items, such as defense phones, aviator goggles, and military helmets [17].

Following the war, the plastics industry returned to normal peacetime production, and production requirements escalated to satisfy the needs of the world. Plastic production became inexpensive because of the large volumes of products required to fulfill companies' orders and laws of scaling. However, at this time, part quality was relatively low because of variations in manufacturing as well as poor designed. These attributes contributed to the negative association that people still have with plastic products [17].

From the late 1950s on, plastics again gained the interest of designers and engineers [35]. Plastics eventually entered into everyday domestic life through a wide range of products, such as Tupperware® which was invented in 1949 by the American manufacturer Tupper [35]. Besides domestic use, the clothing industry exhaustively used polyester, Nylon, and Lycra in its products.

In the 1960s, plastics played an integral role in the “space race” as it gave spacecraft components lightness, high specific strength (strength/density), and versatility [33]. Synthetic polymers have continued to evolve and are found everywhere in our daily surroundings.

1.4 The Structure of Polymers

As discussed, plastics are synthetic polymers. The word *polymer*, which is derived from ancient Greek, means “of many parts.” In Greek, *mer* means “part,” and *poly* means “many.” Similarly, *mono* means “one,” giving the word *monomer* the meaning “of one part.” The simplest definition of a polymer is “a useful chemical made of many repeating units which are known as ‘mers’” [5]. The layering of monomers—which are held together by

strong covalent bonds between molecules—form a polymer, which can be represented as a very long chain. The construction of these molecular chains is polymerization.

Polymer macromolecules have repeating units typically made of carbon, hydrogen, and, sometimes, oxygen, nitrogen, sulfur, chlorine, fluorine, phosphorous, and silicon compounds [5]. The fundamental structure of a polymer chain is called the backbone. Even the most common classifications of polymers have backbones composed of carbon atoms that are bonded together. In addition, carbon atoms can attach one or more different atoms to themselves, thereby creating a more complex polymer with a multidimensional backbone. Examples of polymers containing only carbon and hydrogen atoms are polyethylene, polypropylene, polybutylene, and polystyrene, whose chemical structure can be seen in Figures 10, 11, and 12. Due to the carbon atom in the backbone units, these polymers are classified as organic.

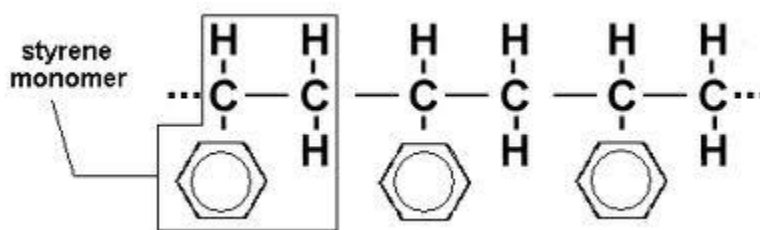


Figure 10. Polystyrene chemical structure [37].

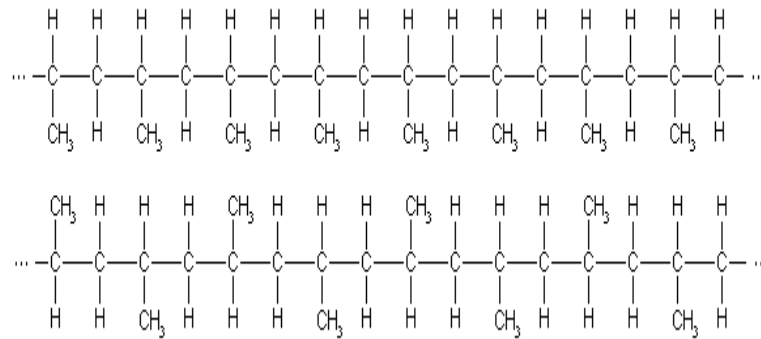


Figure 11. Polypropylene chemical structure [38].

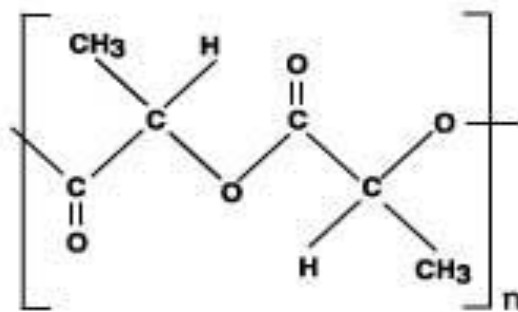


Figure 12. Polylactic Acid (PLA) chemical structure [36].

Variations of previously mentioned organic polymers containing hydrocarbons (HC) include PVC, which binds chlorine to carbon atoms of its backbone, and Teflon®, which binds fluorine to each carbon atom of its backbone. Other examples of organic polymers include nylons that also contain nitrogen in their backbone units and polyester and polycarbonates whose carbon atoms are bound to oxygen atoms. Inorganic polymers have silicon or phosphorus instead of carbon in their backbones [5].

In their molecular structure, polymers can be cross-linked or linear and serve specific needs. The three main types of polymers are thermosets, thermoplastics, and elastomers. Thermosets are plastics with a three-dimensional network in which each chain of the polymer is connected by other chains [55]. The main characteristic of thermosets is that they do not melt once formed. Such polymers are said to be cross-linked or nonlinear.

Other polymers can be two dimensional and defined as branched polymers or one-dimensional linear polymers.

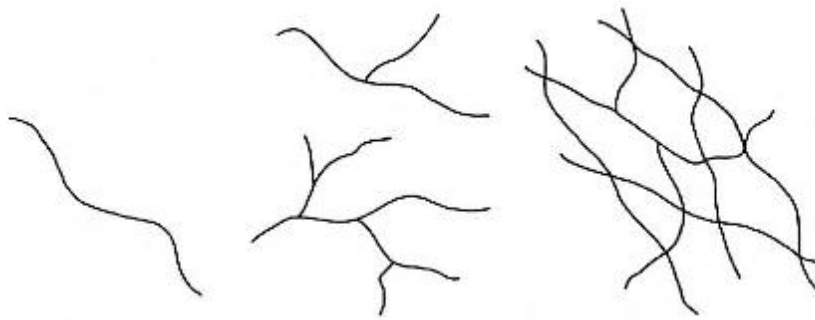


Figure 13. Representative skeletal structures of linear, branch, and cross-linked polymers [54].

Linear polymers are called thermoplastics and have the distinctive feature of being able to re-form over and over after being melted. Most of the plastics produced and consumed are well-known thermoplastics [5], such as plastic bottles, films, cups, and fibers.

Elastomers are cross-linked rubbery polymers (e.g., rubbery networks) that can stretch easily to high extension and rapidly recover their original dimensions when the applied stress is released. The elasticity is the result of the ability of the long chains to reconfigure themselves with the application or removal of stress. The long chains undergo

cross-linking during a process called vulcanization. Vulcanization is the process of making rubber into a more durable material through the addition of sulfur [5]. Elastomers are typically thermoset materials but can also be thermoplastics.

Thermoplastics can be classified according to their degree of crystallinity. A factor that influences the degree of crystallinity is the molecular weight of a polymer, side groups, and processing. This variable measures the length of polymeric chains in a given material and is particularly important because its change determines the final properties of plastics. The molecular weight of plastics is usually between 10,000 and 1,000,000. Thermoplastics with a very high molecular weight are more difficult to form and mold (e.g., they have a high crystallinity [5, 17]). A crystalline arrangement of polymeric chains occurs when the molecules are disposed according to a distinct pattern, (e.g., similar to table salt and gemstone structures). In contrast to high crystallinity materials are amorphous materials. Figure 14 shows the various crystalline structures that plastics can have; the figure shows three distinct layouts.

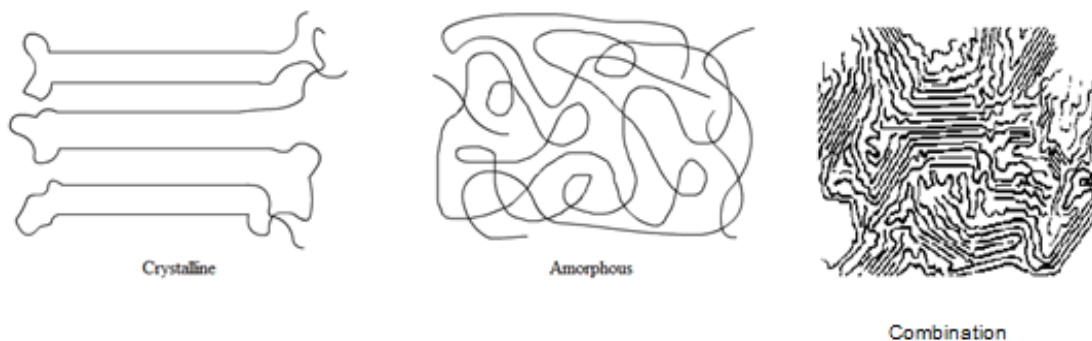


Figure 14. Crystalline structures of plastics [5].

There are some polymers that are completely amorphous, but most are a combination with the tangled, spaghetti looking regions surrounding the crystalline areas.

Amorphous materials have no patterned order, and the arrangement of their polymers could be visually compared to a bowl of disordered spaghetti noodles without any long-range order.

Amorphous polymers are often transparent; this characteristic is particularly important in food wrapping, plastic windows, headlight lenses, and contact lenses. Examples of amorphous plastics are polystyrene and PVC. Nonamorphous (e.g., crystalline) materials are translucent and opaque. Color is not the only characteristic that distinguishes the various levels of crystallinity. Table 2 shows how some common characteristics differ in crystalline and amorphous plastics [17].

Table 2. *Common Characteristics of Crystalline and Amorphous Plastics* [17].

Higher Percentage of Crystalline	Higher Percent of Amorphous
- Higher heat resistance	- Lower heat resistance
- Sharper melting point	- Gradual softening/melting point
- More opaque	- More translucent/transparent
- Greater shrinkage upon cooling	- Lower shrinkage upon cooling
- Reduced low temperature toughness	- Greater low temperature toughness
- Higher dimensional stability	- Lower dimensional stability
- Lower creep	- Higher creep

1.5 Polymers Strengths

According to *American Chemistry* [5], polymers have the distinct characteristics listed below that make them popular for commercial applications:

1. “Resistant to aggressive chemicals—despite the fact that some plastics can be easily dissolved by some solvents, other plastics provide safe and reliable resistance to aggressive chemical solvents (e.g., consider cleaning fluids packaged in plastic or plastic tubes in household’s sewage system). Plastics are also typically weather resistant and are used to substitute materials that would degrade very easily when exposed to the elements of weather [5].
2. Low thermal and electrical conductivity—electrical outlets and wiring are made or covered with polymeric materials, as well as handles on pots and pans, insulated cups, coolers, and microwave cookware. Thermal underwear that many skiers wear are made of polypropylene and the fiberfill in winter jackets is often produced from acrylic and polyester [5].
3. Light in weight but with significant degrees of strength (high specific strength strength/density)—some polymers float in water while others sink (density greater than water) how ever most have densities similar to water. Compared to the density of stone, concrete, steel, copper, or aluminum, however, all plastics are lightweight materials. There are a vast range of light weight yet relatively strong products made from plastics (e.g., from toys to the frame structure of space stations to the Kevlar used in bulletproof vests [5].
4. Easily processed—there are a wide range to process plastics to shape thing into products such as thin polymer fibers, heavy pipes, adhesives, large car panels, drums, paints, highly flexible and stretchable plastics. In addition many can be foamed such as polystyrene, polyurethane, and polyethylene [5].

5. Easily decorated and tailored—Plastics can have a vast amount of range of properties and can emulate, e.g., they can replicate a wide range of other materials, such as wood, porcelain, marble, cotton, silk, and wool-fibers. In addition, additives can enhance their properties and performance [5].
6. Environmental impact—while it may be counter intuitive because of the well known negative impact plastics can have on the environment, plastics can also help save energy consumption in many ways. For example, plastics in car fenders, hoods, trunk lids, and doors, etc., have helped reduce the weight of the average passenger car by 145 pounds since 1988, which has lead to better fuel economy and has helped save an estimated 21 million barrels of oil [47]. These data support the idea of saving fuel by decreasing weight. As an end result, polluting emissions are reduced” [37].

1.6 Plastics Feedstock

The primary raw materials used in producing plastics are petroleum (crude oil), natural gas, and coal. Petroleum is the most commonly used feedstock in the plastics industry today. As of 2009, 4 to 5% of the global oil supply is used as the primary ingredient in plastics production, with an additional 4 to 5% required for energy during manufacturing [46]. OPEC’s cumulative oil production in 2010 was nearly 448 billion barrels [28]. Assuming that 4 to 5% of the global supply is used as plastics feedstock, the total amount of oil employed for plastics would range between 17.9 and 22.4 billion barrels per year (one barrel of oil = 42 U.S. gallons of oil). Factoring in both feedstock supply and energy consumption, the plastics industry requires between 34.8 and 44.8 billion barrels of oil per

year. Due to increasing oil prices and the uncertainty of the extent of remaining oil resources, this presents a major challenge to the plastics industry [19]. While it has been debated, scientists agree that our dependence on crude oil, natural gas, and coal are major reasons for oil shortages and global climate change. For this reason, the United States, along with the rest of the world, must search for alternative raw materials for plastics production.

1.7 Types of Plastics, Plasticizers, and Additives

The classification of plastics depends on their various chemical and physical characteristics. Today, an enormous number of polymeric materials exist, and more than 50 unique families of plastics are in commercial use. Each family has more than a dozen variations [17]. Plastics are seldom used in their pure form. Mixing polymers with other materials called additives alters their characteristics and mechanical properties.

The market is broken down into property modifiers, property stabilizers, property extenders, and processing aids [18]. The primary reasons why additives are used are for: (a) enhancement of polymers' properties and performance, (b) overall cost reduction (e.g., by increasing impact and flame resistance of products, which reduces the probability of having to replace them after short-time use), and (c) improvement and controlling of processing characteristics. Additives may change the mechanical properties of polymers (e.g., strength, elongation, modulus, and toughness) and (d) also their thermal expansion, transparency, and thermal stability [54].

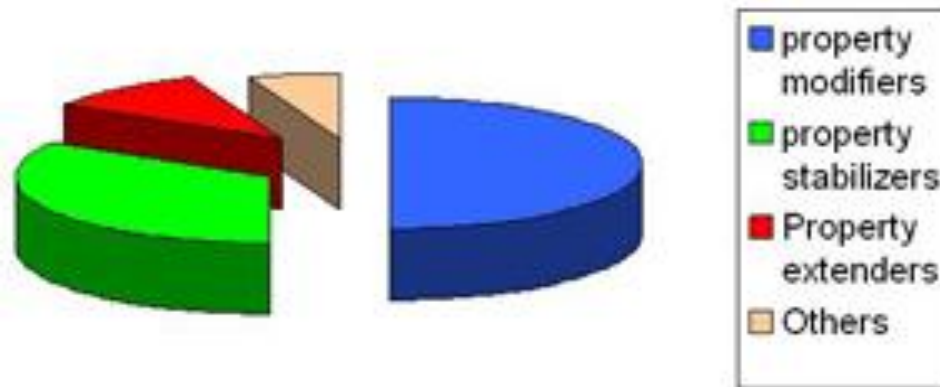


Figure 15. 2009 global additive market [6].

Andrady and Neal state that many different kinds of additives are used, including: (a) fillers (e.g., carbon or silica) to reinforce the plastic material, (b) thermal stabilizers to allow the plastics to be processed at high temperatures, (c) plasticizers to render the material pliable and flexible, (d) blowing agents to produce foamed and expanded plastics, (e) fire retardants to reduce ignition and burning, and (f) UV (ultraviolet light) stabilizers to prevent degradation when exposed to sunlight and UV radiation. Colorants, matting agents, and luster additives may also be used to enhance the appearance of a plastics product [3]. Other types of additives include process aids, lubricants, antioxidants, and heat stabilizers. This list (a thru f) shows that additives are important to improve the efficiency and longevity of plastics [11].

Plastics play an important role in raising the standards of hygiene [23]. PVC has become one of the most important plastics in medicine due to its flexibility, clarity, and sealing properties. It is used in tubing, blood transfusion sets, and disposable packs of equipment. These applications are achieved by using additives that prevented plastic

material from becoming hard and brittle at low temperatures or soft and sticky at high temperatures.

However, plastics and their additives are not always positive. During the degrading process or when plastics are heated, toxic substances can be released [23]. Many scientists agree that those substances can be potentially hazardous to the environment, as well as to human and animal health. Many ongoing discussions and concerns center on substances with an endocrine-disrupting potential. For example, a study by Loyo-Rosales et al. (2004) analyzed the content of nonylphenol (NP) and octylphenol (OP) in plastic bottles made from PET (polyethylene terephthalate), HDPE (high-density polyethylene) and PVC. NP is commonly used as an antioxidant and plasticizer, while OP is typically used as an antioxidant or stabilizer for plastic products. Test results concluded that HDPE and PVC showed a high level of NP, while OP was present in the water of all three types of bottles [23]. These additives are both toxic to humans and animals, particularly for water-residing animals [51].

Numerous attempts have been made to find effective solutions for biodegradability in the decomposition of plastics. Out of all the additives available today, only one “biodegradable plasticizer” exists. It was created to satisfy the need for biodegradability that increased as a result of environmental and legislative pressure to reduce plastic packaging wastes. The need for biodegradable plastics that were compatible with the environment was first satisfied by the introduction of commercial “biodegradable plastics” during the 1990s [26].

Conversely, many plastics are not able to biodegrade; rather, they can only disintegrate [26]. The difference between degradation and biodegradation consists in the fact that degradation stops at the fragmentation stage of polymers. This occurs through the action

of heat, moisture, sunlight, and/or enzymes that shorten and weaken the polymer chains, breaking them apart and eventually leading to cross-linking that creates more intractable persistent residues. During the biodegrading process, the polymers fragments are further processed by microorganisms that consume them as food and as an energy source [26]. Mohee et al. (2008) believe that “the environmental degradability of plastics is a complex process that is influenced by the nature of plastics and the conditions to which they are exposed,” e.g. aerobic and anaerobic conditions. To help avoid confusion, several standards have been developed regarding degradable and biodegradable plastics. U.S. organizations, such as American Society for Testing and Materials (ASTM) and the International Organization for Standardization (ISO), have developed specific standards to help clarify the requirements for degradable and biodegradable plastics. ASTM defines biodegradable plastic materials as a “material having the capability of undergoing decomposition into carbon dioxide, methane, water, inorganic compounds, or biomass predominantly by enzymatic action of microorganisms” [7]. Additionally, ASTM requires a decomposition rate of 60% to 90% of the plastic material within 60 to 180 days in a composting environment [7].

Today, many different types of biodegradable plastics are available. The first classification is according to the plastic materials feedstock, which can be broken into two categories, petroleum-based synthetic resins or bioplastics. Bioplastics are usually considered to be plastics derived from natural resins, such as starch, cellulose, vegetable oils, and sugars [15]. Once the feedstock is harvested, it is manufactured into lactic acid (or other less common fundamental building blocks), which is a monomer produced by microorganisms. This monomer can be polymerized to polylactic acid (PLA) [42]. Even if

bioplastics are advertised as “natural plastics,” their starch content may vary between 5% and 90%. The remaining percentages are synthetic materials, additives, or plasticizers. Due to this wide range, Davis and Song (2006) proposed to change the name of biodegradable plastics from “starch-based polymers” to “starch-containing biodegradable polymers,” in case the starch-content is lower than 50% [13]. It is important to remember that some petrochemical plastics are considered biodegradable. Traditional plastics, such as polyethylene, are degraded by ultraviolet light and oxygen. To help prevent this, stabilizing chemicals are added during manufacturing. Further, not all bioplastics break down; polyethylene derived from sugarcane breaks down at such a slow rate that it is considered nonbiodegradable. The third way of classifying bioplastics is by their method of decomposition. This includes photo and oxodegradation, compost degradation, hydrobiodegradation, and bioerodible plastics. According to Mohee and Unmar (2007), the usual biodegradation time required for bioplastics to be composted is one to six months [27].

1.8 Dent Corn

One of the most important crops required to make polylactic acid (PLA) is corn. According to Purdue University horticulture scientists, “Native Americans began growing corn over 5600 years ago, originating in an area known as Mesoamerica which extends from Central America to northern Mexico” as seen in Figure 16 [12].

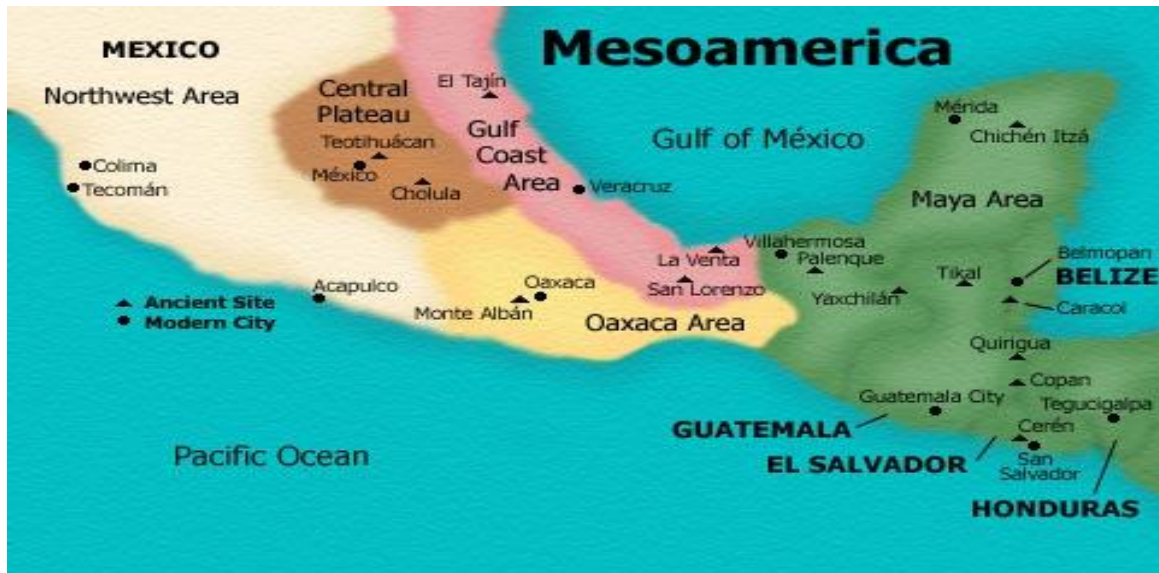


Figure 16. Map of Mesoamerica [25].

“Dent corn, the most widely used corn in the manufacturing of PLA due to the availability and since it is higher in starch and lower in sugar than other types of corn. Dent corn provides corn starch which is the most widely used portion of the kernel in bio-plastic production” [5]. A corn kernel is made up of four major components: starch, fiber, protein, and oil. Starch and other byproducts can be processed into an assortment of things from biodegradable plastics to fuels [44]. The hull is the outside layer of the corn kernel; this protects the kernel from breaking down or being damaged. Starch, which is used for the manufacture of plastics, is stored in the endosperm. Another major component to the corn kernel is the germ; this is located toward the bottom of the kernel.

These parts of the kernel can be seen in Figure 17.

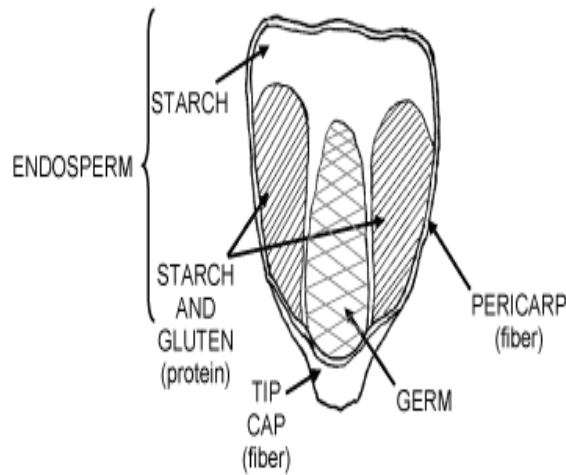


Figure 17. Structure of the corn kernel [50].

1.9 Manufacturer of Plastic Products

The most widely used plastic molding methods are injection molding, blow molding and profile extrusion. Plastic molding dates to the late 1800s, but the first extrusion machine was created by Bramah in 1797 to extrude lead pipe, with the addition of copper and brass alloys in 1894 by Dick. Injection molding also dates back to 1872, when Hyatt and Hyatt patented the first injection molding machine [24]. Another inventor named Hendry expanded the injection molding industry in the 1940s, as World War II created a huge demand for inexpensive, mass-produced products. In 1946, Hendry built the first screw injection machine, which allowed much more precise control over the speed of injection and the quality of articles produced. Extrusion, which is primarily used in processing thermoplastics (as well as selected thermosets) and other composite materials, is based on the ancient principle of the Archimedes screw [26]. The screw was originally invented to move water for irrigation and was later utilized to reclaim land that was under sea level in the

Netherlands. The Archimedes screw also served in the creation of polders, which are low-lying tracts of land enclosed by embankments. The plastics industry adopted the screw mechanism in its machines to help with plasticizing, pumping, and mixing during polymer processing [49].

Blow molding was founded on the similar philosophy as glass blowing. The first machine was produced by Ferngren and Kopitke in 1937. During the 1940s, the number of products that could be blow molded was limited, which restricted its commercial acceptance. The increase in the variety of products and production rates resulted in an increase in the numbers of each product. In the United States, the soft drink industry went from zero blow-molded bottles in 1977 to ten billion bottles in 1999 using this method. Today, an even a greater number of products are blown, and this number is expected to keep increasing [24].

1.9.1 Extrusion

Plastic extrusion is a high-volume manufacturing process in which raw plastic material is melted (plastized) and formed into a continuous profile. Extrusion produces a variety of products, such as pipe/tubing, weather stripping, fence, deck railing, window frames, adhesive tape and wire insulation [16].

During extrusion, the raw thermoplastic or thermoset material, which is in the form of small beads (often called resin in the industry), is gravity fed from a hopper mounted on top of the machine into the barrel of the extruder. Additives, such as colorants and UV inhibitors (in either liquid or pellet form), are often used and can be mixed into the resin prior to arriving at the hopper or at the hopper [16].

The material then enters through the feed throat (an opening near the rear of the barrel) and comes into contact with the screw. The rotating screw (normally turning between 15 to 120 rpm) forces the plastic beads forward into the barrel which is heated to the desired melt temperature of the molten plastic (which can range from 200 °C [392 °F] to 275 °C [527 °F] depending on the polymer). In most processes, a heating profile is set for the barrel in which three or more independent proportional–integral–derivative (PID) controlled heater zones gradually increase the temperature of the barrel from the rear (where the plastic enters) to the front. This allows the plastic beads to melt gradually as they are pushed through the barrel and lowers the risk of overheating which may cause degradation in the polymer [17].

While the heater bands are needed for the initial startup of the machine, between 75% and 85% of the temperature is generated by friction inside the barrel. If an extrusion line is running a material fast enough, the heaters can be shut off, and the melt temperature can be maintained by the pressure and friction alone inside the barrel. In most extruders, cooling fans keep the temperature below a set value if too much heat is generated. If forced air cooling proves insufficient, then cast-in cooling jackets are employed. They generally use a closed loop of distilled water in heat exchange with tower or city water [17].

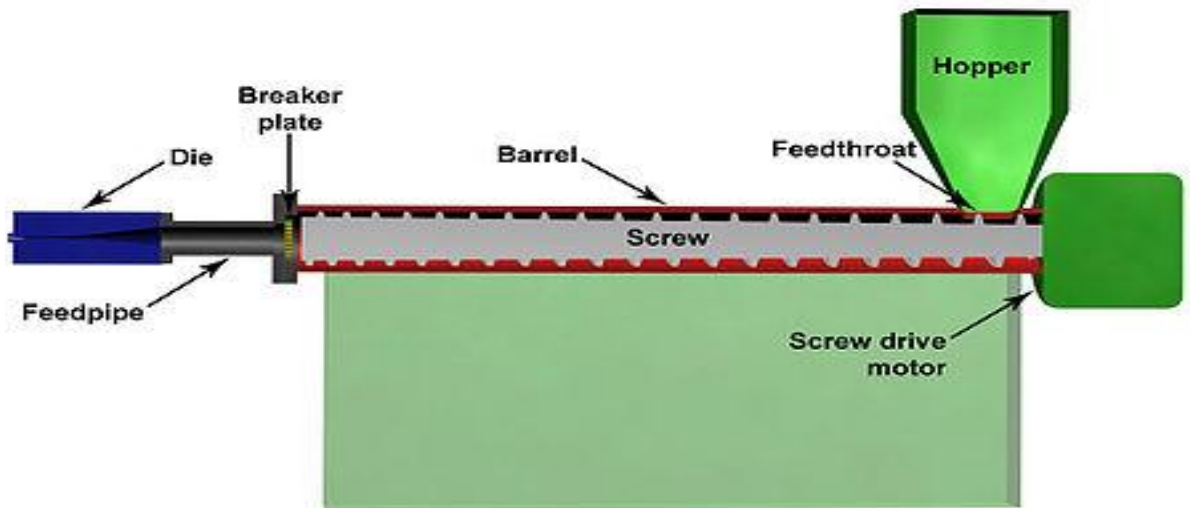


Figure 18. Layout of a plastic extrusion machine [21].

At the front of the barrel, the molten plastic leaves the screw and travels through a screen pack to remove any contaminants in the melt. The screens are reinforced by a breaker plate (a thick metal puck with many holes drilled through it) because the pressure at this point can exceed 5000 psi (34 MPa). The screen pack/breaker plate assembly also serves to create back pressure in the barrel. Back pressure is required for uniform melting and proper mixing of the polymer. This breaker plate and screen pack combination initiates the converting of "rotational memory" of the molten plastic into "longitudinal memory" [17].

After passing through the breaker plate, the molten plastic enters the die. The die is what defines the final product's profile and must be designed so that the molten plastic flows evenly from a cylindrical profile to the product's profile shape. Uneven flow at this stage would produce a product with unwanted stresses at certain points in the profile. These stresses can cause warping upon cooling. Almost any shape imaginable can be created [16].

The product must then be cooled, which is usually achieved by pulling the extruded part through a water bath. Plastics are very good thermal insulators and are therefore difficult to cool quickly. Compared to steel, plastic conducts its heat away 2000 times more slowly [16]. In a tube or pipe extrusion line, a sealed water bath is acted upon by a carefully controlled vacuum to keep the newly formed and still molten tube or pipe from collapsing. For products such as plastic sheeting, the cooling is achieved by pulling through a set of cooling rolls [16].

1.9.2 Injection Molding

Injection molding, which plastizes the plastic with an extruder, then forces the molten plastic into a mold with defined cavities.

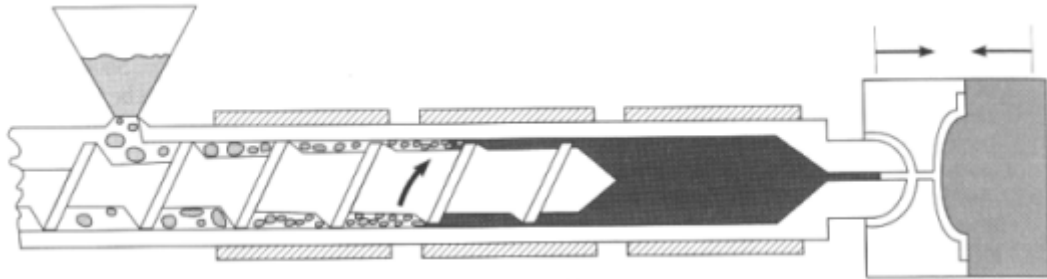


Figure 19. Layout of reciprocating screw and barrel in plastic injection molding machine [8].

The resin is injected into the mold by a reciprocating screw or a ram injector. The reciprocating screw apparatus is shown in Figure 19. The reciprocating screw offers the advantage of mixing the plastic better. With the reciprocating screw, the melt is thoroughly mixed, resulting in a homogenous (uniform) melt. Much of this is attributed to being able to

hold a temperature variation of ± 7 degrees. In addition, it allows for higher injection pressures, faster injection speeds, and shorter molding cycles [8].

The mold is the part of the machine that receives the plastic and shapes it appropriately. The mold is cooled constantly to a temperature that allows the resin to solidify. The mold plates are held together by hydraulic or mechanical force. The clamping force is defined as the injection pressure multiplied by the total cavity projected area. Typically molds are oversized depending on the resin to be used. Each resin has a calculated shrinkage value associated with it [8].

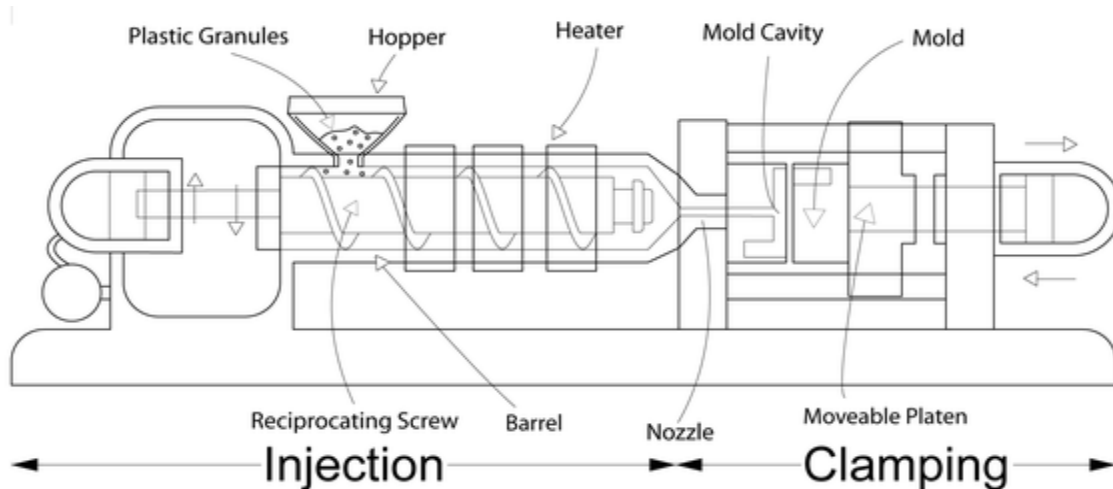


Figure 20. Layout of plastic injection molding machine [22].

1.9.3 Blow Molding

Blow molding, also known as blow forming, is a manufacturing process by which hollow plastic parts are produced. Typically plastic bottles, jugs and jars are formed using

this process. In general, there are three main types of blow molding: extrusion blow molding, injection blow molding, and stretch blow molding [24].

1.9.3.1 Extrusion Blow Molding

Extrusion blow molding is possibly the simplest type of blow molding. A hot tube of plastic material is gravity feed from an extruder and captured in a water-cooled mold. Once the molds are closed, air is injected through the top or the neck of the container. When the hot plastic material is blown to match the walls of the mold, the material "freezes."

Extrusion blow molding allows for a wide variety of container shapes, sizes, and neck openings, as well as the production of handle ware. Extrusion blow molds are generally less expensive than injection blow molds and can be produced in a much shorter period of time.

The extrusion blow molding process is illustrated in Figure 21 [24].

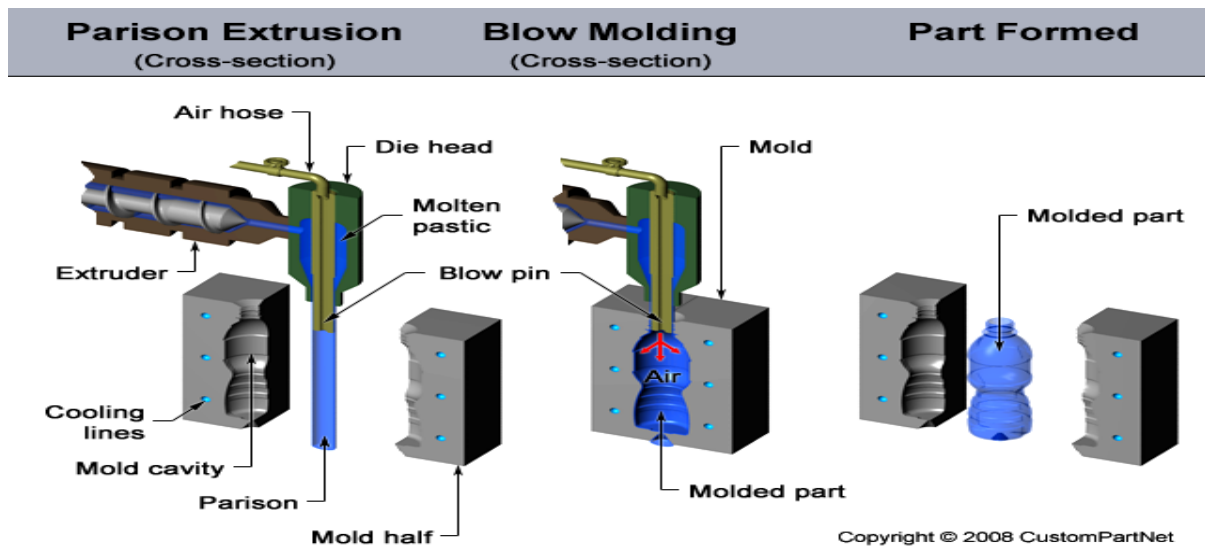


Figure 21. Plastic blow molding process [30].

1.9.3.2 Injection Blow Molding

Injection blow molding is a combination of injection molding and blow molding. With injection blow molding, the hot plastic material is first injected into a cavity where it encircles the blow stem, which is used to create a preform which often has threads for the sealing of the final product. The preform (the parison) is then blown in a separate machine into the finished container, as in the extrusion blow molding process above. Injection blow molding is generally not suitable for smaller containers [24].

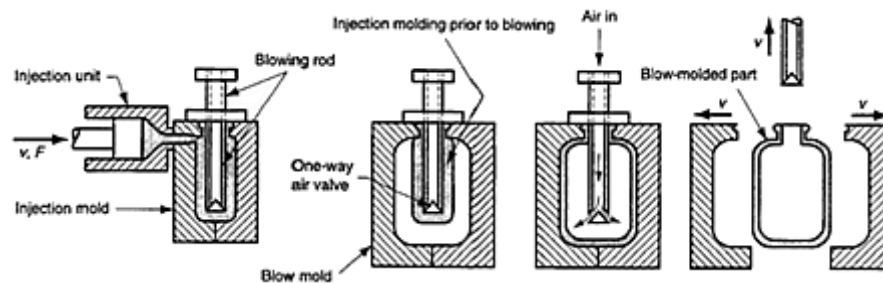


Figure 22. Plastic injection blow molding process [32].

1.9.3.3 Stretch Blow Molding

Stretch blow molding is best known for producing P.E.T. bottles commonly used for water, juice, and a variety of other products. There are two processes for producing stretch blow molded P.E.T. containers. In one process, the machinery injection molds a preform, which is then transferred within the machine to another station where it is blown and then ejected. This type of machinery is generally called injection stretch blow molding (ISBM) and usually requires large runs to justify the very expense of the injection molds that create

the preform and the blow molds that finish the blowing of the container [24]. This process is used for extremely high-volume (multimillion) runs of items such as wide-mouth peanut butter jars, narrow-mouth water bottles, liquor bottles, etc. Figure 23 shows how the stretch blow molding process works with the bottom portion of indicating how the stretching takes place [24].

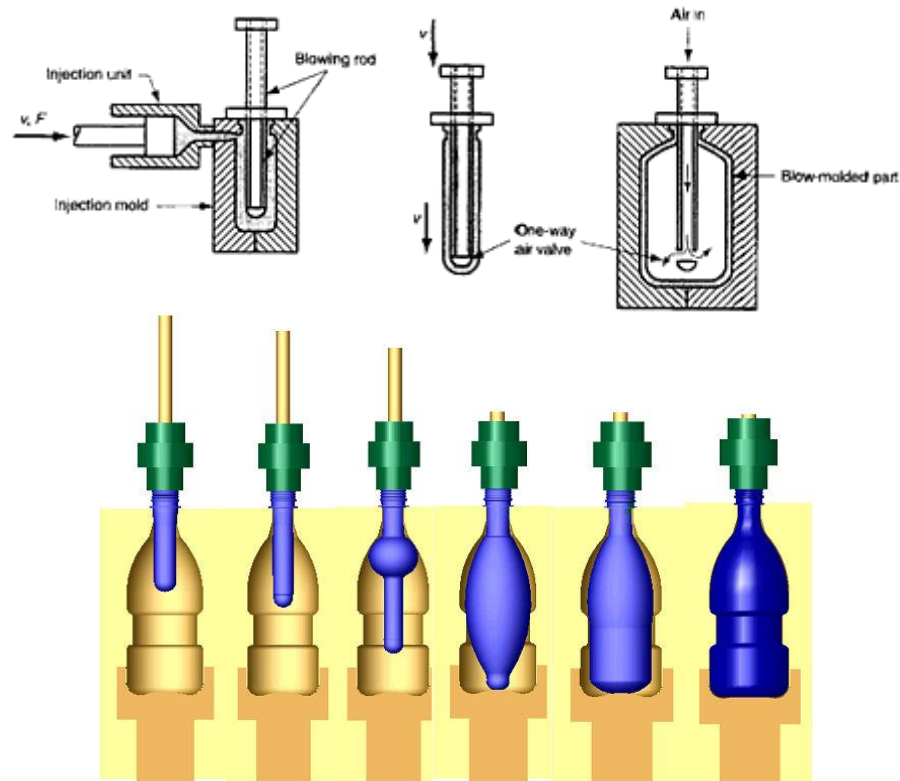


Figure 23. Plastic stretch blow molding process [32].

1.10 Background of the Study

President Barack Obama signed Executive Order 13514 Federal Leadership in Environmental, Energy, and Economic Performance (EO 13514) in October 2009. This order requires the Federal government to be a leader in sustainability and environmental

impact reduction. Cafeterias and food service within the government have been identified as areas of opportunity for sustainability initiatives and disposable cutlery has been identified as a possible area for the use of recyclable or compostable alternatives [52].

The BioPreferred Program, established in 2002 as a result of the Farm Security and Rural Investment Act of 2002 and later expanded because of the signing of EO 13514, helps guide the U.S. government in the purchase of products made from biorenewable materials. The BioPreferred Program has two main foci, the first of which is product labeling. The United States Department of Agriculture (USDA) “certifies and awards labels to qualifying products and companies to increase consumer recognition of biobased products” [52]. The second goal is to give guidance in the Federal Procurement Preference. This means that there are “categories of biobased products that are the afforded preference by Federal agencies when making purchasing decisions” [52].

Researchers at the Iowa State University Center for Industrial Research and Service (CIRAS) are investigating biobased products through a cooperative agreement with the USDA. CIRAS has been asked by the USDA to provide information regarding the performance, cost, and end-of-life claims of biobased disposable cutlery. Many researchers, as well as CIRAS staff, had already observed that a perceived weakness of biobased cutlery was its flexibility. To address this perception, CIRAS identified the General Services Administration (GSA) Commercial Item Description (CID) A-A-3109B "Fork, Knife, and Spoon, Picnic (Plastic)" specification to which disposable cutlery must adhere in order to be eligible for Federal purchase and compared biobased products with these specifications. Within the CID is a maximum deflection tolerance, which is the main focus of this study.

The GSA is an independent agency of the United States government, which was established in 1949 by President Truman to help streamline the administrative work of the federal government [1]. The original mission of GSA was to help dispose of surplus war goods, manage and store government records, handle emergency preparedness, and stockpile strategic supplies for wartime. Today, the GSA provides workspace to more than one million federal civilian workers, oversees the preservation of 425 historic buildings, and facilitates the purchase of high-quality, low-cost goods and services from commercial vendors [1].

1.11 Objective

Two objectives were identified as within the scope of this project. The first was to determine if biobased cutlery meets the flexibility specifications defined in the CID. The second was to compare the relative performance of biobased and conventional (petrochemical-based) disposable cutlery. For the purposes of this study, biobased cutlery has been defined as any commercially available disposable cutlery composed in whole or in significant part of agricultural (including plant, animal, and marine materials) or forestry materials. Conventional cutlery includes any commercially available disposable cutlery that does not claim to be made of biobased materials in the product description [48].

CHAPTER 2. METHODS

2.1 Equipment and Materials

The overall test cell to determine the flexibility of the utensils is seen in Figure 24.

The individual components are detailed alongside:

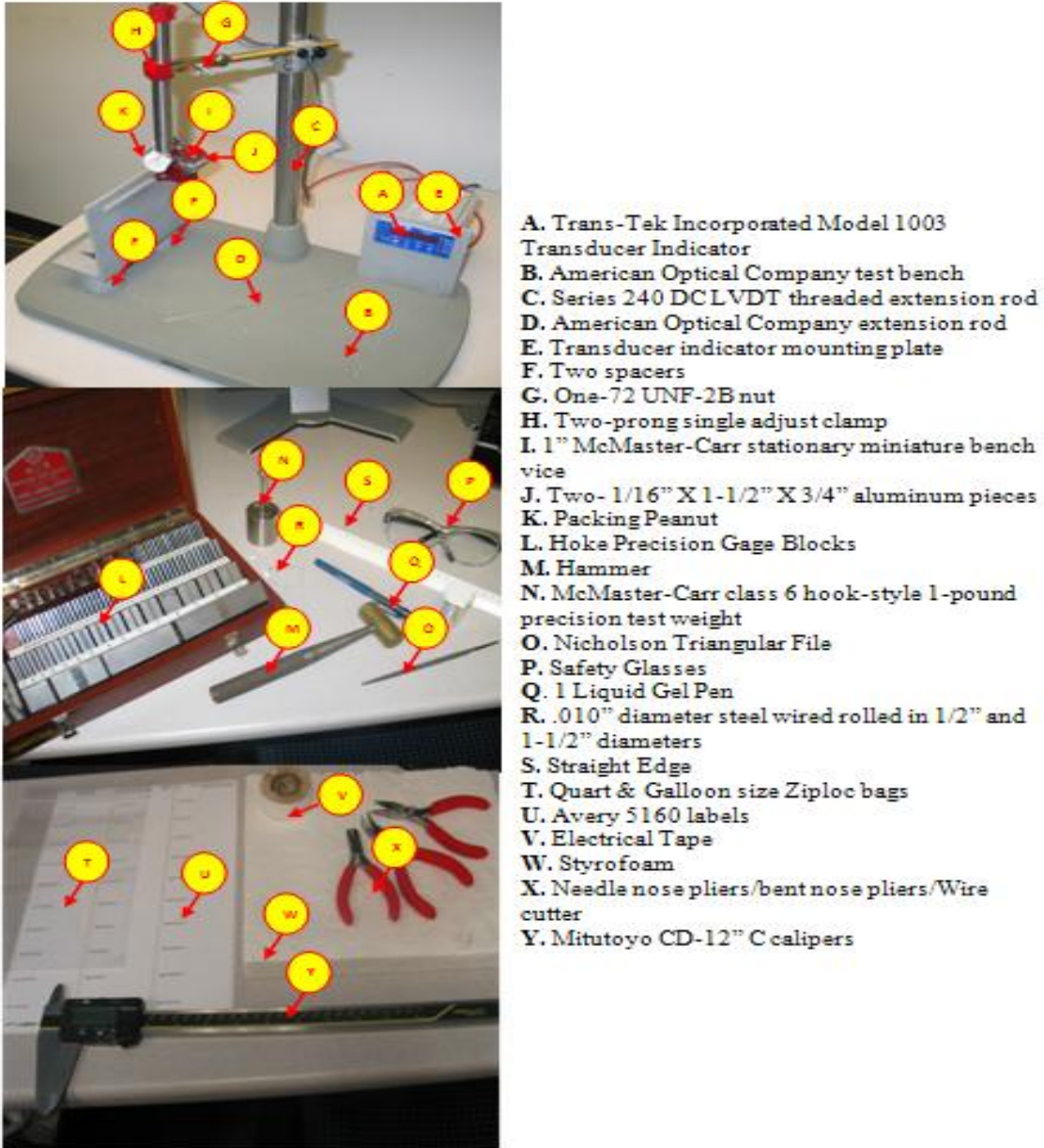


Figure 24. Equipment and materials.

The overall experimental procedures are detailed in Sections 2.2 to 2.5.

2.2 Procedure

A linear variable differential transformer (LVDT) is a moving core (translation device) used for measuring linear displacement. The transformer has three solenoid coils placed end to end around a translating metal core. The center coil is the primary, and the two outer coils are the secondaries. The cylindrical magnetic core, attached to the object which is to be measured, slides along the axis of the tube. The transfer of current between the primary and the secondaries of the LVDT displacement transducer is controlled by the position of a magnetic core called an armature. At the center of the position measurement stroke, the two secondary voltages of the displacement transducer are equal, but because they are connected in opposition, the resulting output from the sensor is zero.

As the core moves, these mutual inductances change, causing the voltages induced in the secondaries to change. The coils are connected in reverse series, so that the output voltage is the difference (hence "differential") between the two secondary voltages. When the core is in its central position, equidistant between the two secondaries, equal but opposite voltages are induced in these two coils. As a result, the output voltage is zero. When the core is displaced in one direction, the voltage of one of the other coils increases while the other decreases. This causes the output voltage to increase from zero to its maximum value. When the core moves in the other direction, the output voltage also increases from zero to a maximum, however the phase is opposite to that of the primary. The phase of the voltage

indicates the direction of the displacement. The sliding core whose relative position is held by the magnetic core does not touch the inside of the tube; it can move without friction, making the LVDT a highly reliable device. The strength of the LVDT sensor's principle is that there is no electrical contact across the transducer position sensing element, which means cleaner data and more precise measurements.

LVDTs are commonly used for position feedback in servomechanisms and for automated measurement in machine tools (i.e., coordinate measuring machines) and many other industrial and scientific applications [41]. In this study, the LVD was used to measure the displacement (deflection) of the utensils under a preselected load.

The GSA's Commercial Item Description: Fork, Knife, and Spoon, Picnic Plastic specifies that the accuracy of the DC LVDT and the transducer indicator must be tested at the start of each day and must be placed on a level surface. In addition, the transducer indicator must be turned on for thirty minutes prior to the start of testing. The GSA also states that each utensil must meet the deflection requirements detailed in Table 3. Any deflection greater than the values detailed in Table 3 results in failure of the product.

Table 3. *GSA- allowed maximum deflection.*

Utensil Type	Maximum Deflection (mm)
Fork	22.2
Knife	38.1
Spoons, tea	25.4

Steps for calibration can be found on page 16 of the Trans-Tek Incorporated Model 1003 Transducer Indicator instruction manual. Hoke Precision Gage Blocks were used for accuracy/calibration testing. After calibrating, the Hoke Precision Gage Blocks were removed, and Styrofoam® was used to protect the test bench from the 4.44 N weight, which is the defined weight for testing by the standard A-A-3109B Fork, Knife, and Spoon, Picnic (Plastic).

Before performing the tests, each utensil must be labeled with a code consisting of the item number (Fk, Fork; Sp, Spoon; and Kn, Knife), the company letter, the test number (5212-5215, as outlined in the CID) [50], and the trial number (1-15 for each brand of each test (each brand was tested 15 times). To establish statistical validity of the testing results, a population of fifteen samples was tested. An outlier (company with 89% biobased content) was discarded on a second analysis because the amount of biobased content was higher (89%) than that of the remaining twelve companies tested in which every company was between 45% and 52% biobased content.

The environmental conditions during testing were a relative humidity (Rh) between 30% to 50% and testing temperatures from 20°C to 25°C, as defined by the standard. The CID states that the utensil shall be conditioned at $22.7^{\circ}\text{C} \pm 12.7^{\circ}\text{C}$ and $50 \pm 4\%$ relative humidity for 48 hours prior to testing.

2.3 Fork Testing Procedure

After calibration of the LVDT, the samples were prepared according to the following steps. Calibration was performed at the start of every shift or after long breaks.

Step 1

A straight line was marked across the base of the fork tines, and a second line was placed two inches (50.8 mm) from the first line, as seen in Figure 25. The second line was used as a location when the fork was later placed in the vise for testing.

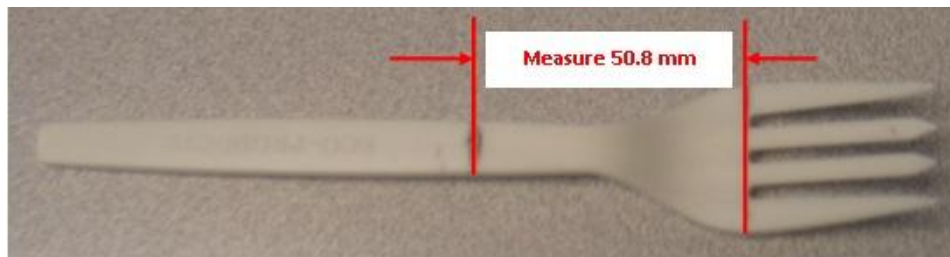


Figure 25. Step 1 fork layout.

Step 2

With the concave surface facing up, small notches are made at the edges of the fork at the base of the tines, as seen in Figure 26. This was completed manually using a triangular file, and the depth was approximately .254 mm X .254 mm.

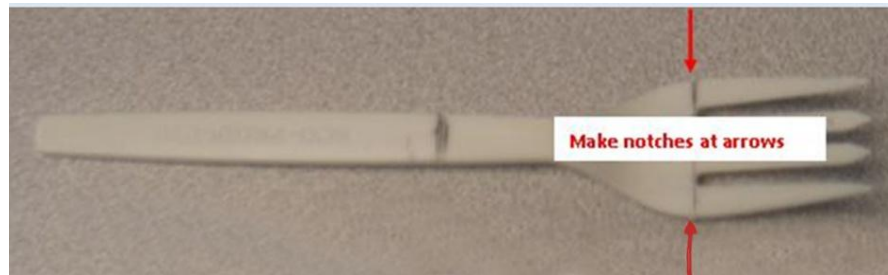


Figure 26. Step 2 fork layout.

Step 3

Reconfirm the calibration of the LVDT with gage blocks. The LVDT displacement rod should then be secured with a packing peanut (or soft material) to prevent damage to the rod in a position that is clear from the vise and sample, as seen in Figure 27.



Figure 27. Step 3 fork layout.

Step 4

The fork was then secured in the vise jaws so that the front edge of the vise was aligned with the second line marked on the fork in step 1. When the fork is in the correct position, the vise jaws are finger tightened snugly so the utensil would not slide.

Step 5

The LVDT rod was released from the packing peanut and placed on the first line shown in Figure 28.

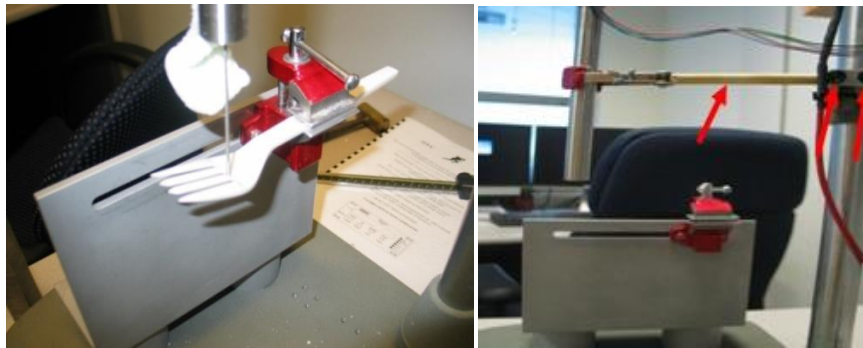


Figure 28. Step 5 fork layout.

Step 6

The LVDT transducer indicator was zeroed.

Step 7

The fork was removed from the vise, and gage blocks were placed below the LVDT rod, as shown in Figure 29. The LVDT rod was placed on top of the gage blocks, and the distance as indicated by the unit was verified. This served as a poka yoke to ensure that the calibration worked correctly. This only occurred at the start of each test sample (one time per company).

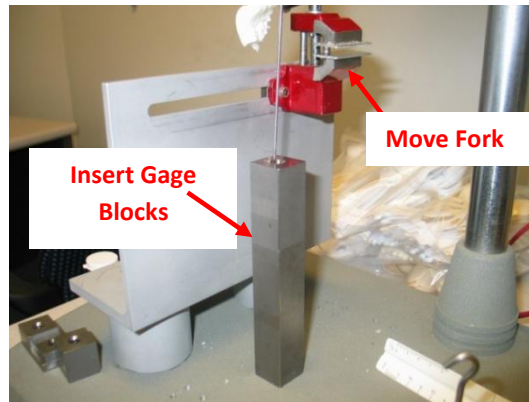


Figure 29. Step 7 fork layout.

Step 8

The fork was replaced in the vise jaws, which were tightened. Care was taken to ensure the same position as in step 5. The same placement was confirmed by ensuring that the LVDT position was zero, as in step 6. The wire with the weight was securely in the notches made in step 2, as seen in Figure 30.



Figure 30. Step 8 fork layout (LVDT rod is touching the wire; wire is pulled flush against the utensil).

Step 9

After taking the reading on the LVDT digital screen, the LVDT rod was again secured away from the setup with a packing peanut, the weight was removed from the fork, the fork was removed from the vise jaws, and the reading was recorded in a spreadsheet.

Deflection greater than 22.2 mm resulted in a FAILURE.

Step 10

Put a label on the fork handle and place in a bag.

2.4 Knife Testing Procedure

After calibration of the LVDT, the samples were prepared according to the following steps. Calibration was performed at the start of every shift, or after long breaks.

Step 1

A straight line was marked 101.6 mm from the cutting end of the knife, as seen in Figure 31. The line (101.6 mm from the cutting end) was used as a location when the knife was later placed in the vise for testing.

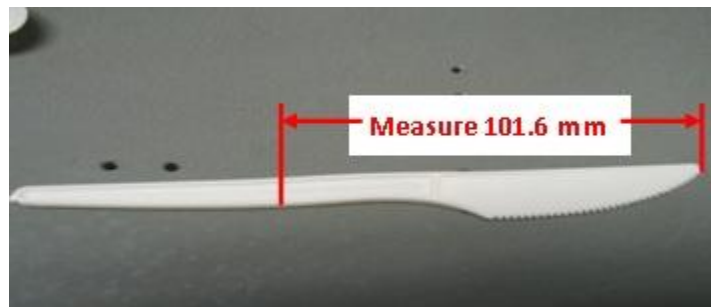


Figure 31. Step 1 knife layout.

Step 2

A second line was measured 88.9 mm from the line that was marked in step 1 (toward the cutting end of the knife). This line indicated where the weight was placed on the knife. After the line was marked, small notches were made at the edges of the knife at the base of the tines, as seen in Figure 32. This was completed manually using a triangular file, and the depth was approximately 0.254 mm by 0.254 mm.

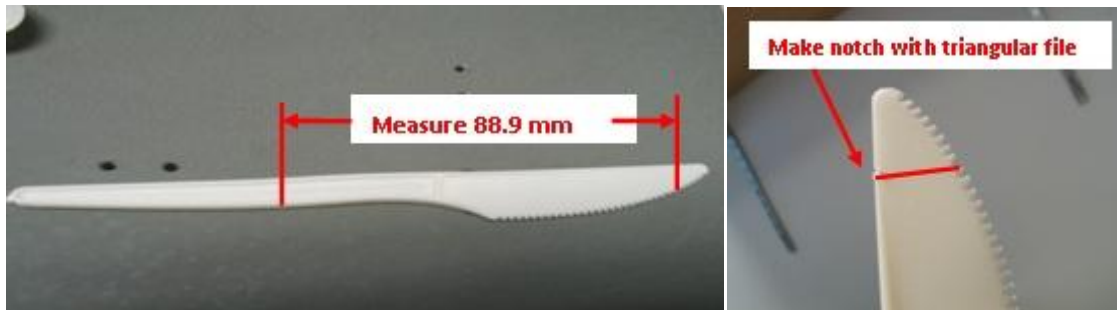


Figure 32. Step 2 knife layout.

Step 3

Reconfirm the calibration of the LVDT with gage blocks. The LVDT displacement rod should then be secured with a packing peanut (or soft material) to prevent damage to the rod in a position that is clear from the vise and sample, as seen in Figure 33.



Figure 33. Step 3 knife layout.

Step 4

The knife was then secured in the vise jaws so that the front edge of the vise was aligned with the line on the knife from step 1 (108.6 mm from the cutting end of the knife). When the knife was in the correct position, the vise jaws were finger tightened snugly so the utensil would not slide.

Step 5

The LVDT rod was released from the packing peanut and placed on the second line on the knife, as seen in Figure 34.

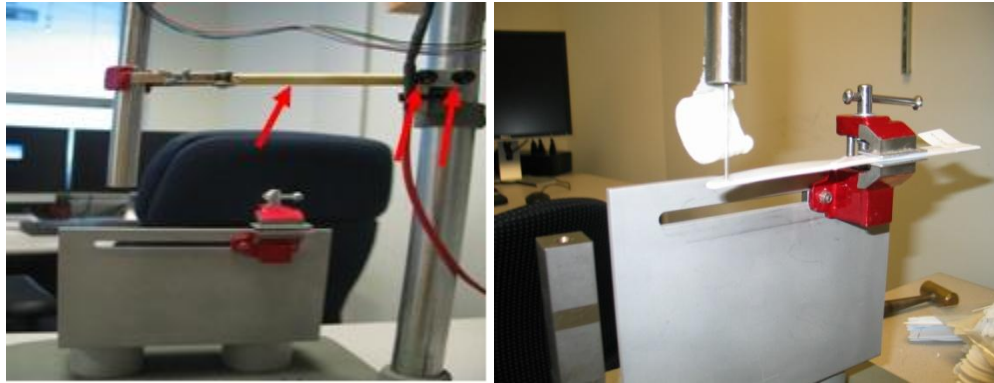


Figure 34. Step 5 knife layout.

Step 6

The LVDT transducer indicator was zeroed.

Step 7

The knife was removed from the vise, and gage blocks were placed below the LVDT rod, as shown in Figure 35. The LVDT rod was placed on top of the gage blocks, and the distance as indicated by the unit was verified. This served as a poka yoke to ensure that the calibration worked correctly. This only occurred at the start of each test sample (one time per company).

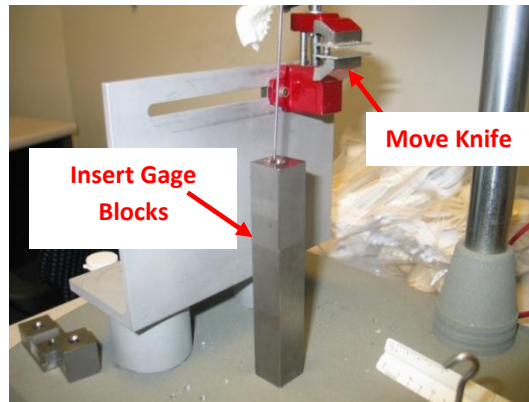


Figure 35. Step 7 knife layout.

Step 8

The knife was replaced in the vise jaws, which were tightened. Care was taken to ensure the same position as in step 5. The same placement was confirmed by ensuring that the LVDT position was zero, as in step 6. The wire with the weight was securely in the notches made in step 2, as seen in Figure 36.

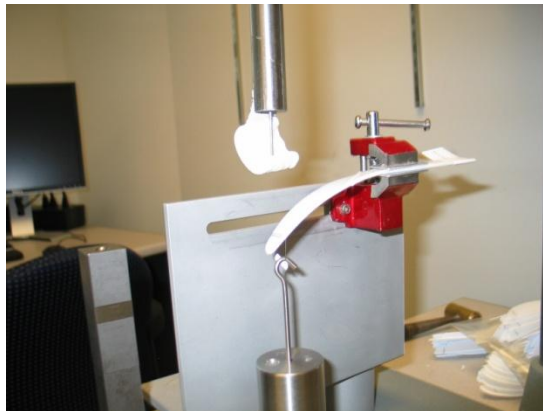


Figure 36. Step 8 knife layout (LVDT rod is touching the wire; wire is pulled flush against the utensil).

Step 9

After taking the reading on the LVDT digital screen, the LVDT rod was again secured away from the setup with a packing peanut, the weight was removed from the knife, the knife was removed from the vise jaws, and the reading was recorded in a spreadsheet.

Deflection greater than 38.1 mm resulted in a FAILURE.

Step 10

Put a label on the knife handle and place in a bag.

2.5 Spoon Testing Procedure

After calibration of the LVDT the samples were prepared according to the following steps. Calibration was performed at the start of every shift, or after long breaks.

Step 1

A caliper was used to measure the widest part of the spoon bowl, and a straight line was marked on both sides the spoon, as seen in Figure 37.



Figure 37. Step 1 spoon layout.

Step 2

A second line was measured 82.5 mm from the line that was marked in step 1 (toward the spoon handle). This line indicated where the weight was placed on the spoon. After the line was marked, small notches were made at the edges of the spoon bowl, as seen in Figure 38. This was completed manually using a triangular file, and the depth was approximately 0.254 mm by 0.254 mm.



Figure 38. Step 2 spoon layout.

Step 3

Reconfirm the calibration of the LVDT with gage blocks. The LVDT displacement rod should then be secured with a packing peanut (or soft material) to prevent damage to the rod in a position that is clear from the vise and sample, as seen in Figure 39.

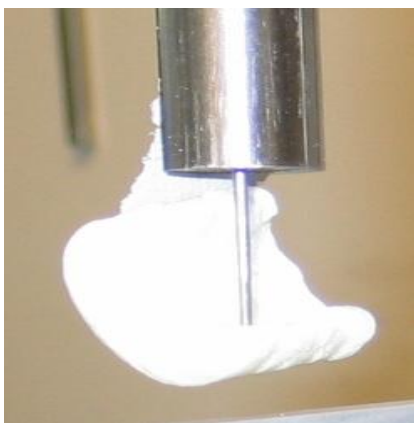


Figure 39. Step 3 spoon layout.

Step 4

The spoon was then secured in the vise jaws so that the front edge of the vise aligned with the line on the spoon from step 2 (82.5 mm from the widest part of the spoon bowl). When the spoon was in the correct position, the vise jaws were finger tightened snugly so the utensil would not slide.

Step 5

The LVDT rod was released from the packing peanut and placed on the first line on the spoon, as shown in Figure 40.



Figure 40. Step 5 spoon layout.

Step 6

The LVDT transducer indicator was zeroed.

Step 7

Move the spoon out of the way so the LVDT rod can slide up and down freely, then place a set of gage blocks underneath the LVDT rod and, this is shown in *Figure 41*.

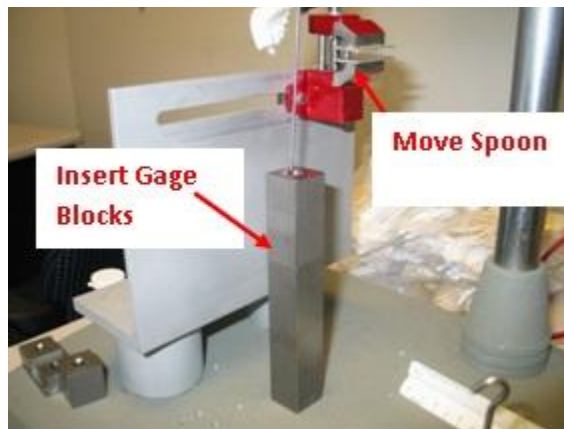


Figure 41. Step 7 spoon layout.

Step 8

The fork was replaced in the vise jaws, which were tightened. Care was taken to ensure the same position as in step 5. The same placement was confirmed by ensuring that

the LVDT position was zero, as in step 6. The wire with the weight was securely in the notches made in step 2, as seen in Figure 42.



Figure 42. Step 8 spoon layout.

Step 9

After taking the reading on the LVDT digital screen, the LVDT rod was again secured away from the setup with a packing peanut, the weight was removed from the fork, the fork was removed from the vise jaws, and the reading was recorded in a spreadsheet.

Deflection greater than 22.5 mm resulted in a FAILURE.

Step 10

Put a label on the spoon handle and place in a bag.

2.6 Finite Element Analysis

Finite Element Analysis (FEA) models were constructed to compare the deflection for conventional and biobased utensils using Solidworks FEA solver. FEA is defined by

Zecher of Indiana-Purdue University as a “computer based numerical technique that is used to solve stress analysis, heat transfer, fluid flow and other types of engineering problems [58]. Finite Element Analysis involves portioning of a structure into a finite number of elements. Elements are connected to one another at their corner points which are called nodes. Each element is a shape, such as a triangle or quadrilateral. Being a standard shape facilitates the development of the governing equations that relate to the displacement of stress and behavior within the element” [58]. In order to define a finite element model, things such as nodes, elements, loads, supports and material properties must be defined. In addition, a solid model is required. In this case models were generated by reverse engineering existing utensils with a three dimensional modeling system to generate a file that could be imported into Solidworks 3D modeling software. The boundary conditions were zero degrees of freedom and the clamping locations, linear material properties and a static load at the edge of the utensils corresponding to the location of the string that applied the load.

Table 4 shows the mechanical properties of the selected resins that were used to compute the FEA models. These numbers were obtained from the resins technical data sheets.

Table 4. *Mechanical properties of materials analyzed using FEA (SI units).*

Material	Density (g/cm ³)	Poissons Ratio	Elastic Modulus (Pa)	Yield Strength (Pa)
500W Polystyrene	1.04	0.3	450,000	44,126,446
2003D Ingeo PLA	1.24	0.3	500,000	59,984,388

2.7 Creep Testing

Creep testing on both polystyrene and PLA were completed using ASTM Standard D2990-09 Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics. Testing was only done on polystyrene and PLA because these were the only materials that could be obtained from a utensil manufacturer. American Chemistry defines creep as the tendency of a solid material to slowly move or deform permanently under the influence of stresses [5]. Deformation is defined by American Chemistry as “the change in the shape or dimensions of a body, resulting from stress; strain” [5]. This can be attributed to the different mechanical properties associated with each material.

To measure the creep of the materials, a 4.44 N load was placed on a dogbone sample whose extension was measured with an extensometer from an Instron machine. The dogbone sample was made using an injection molding machine that had a mold cavity with the dimensions shown in Figure 43. A photo of the creep rig can be seen in Figure 44.

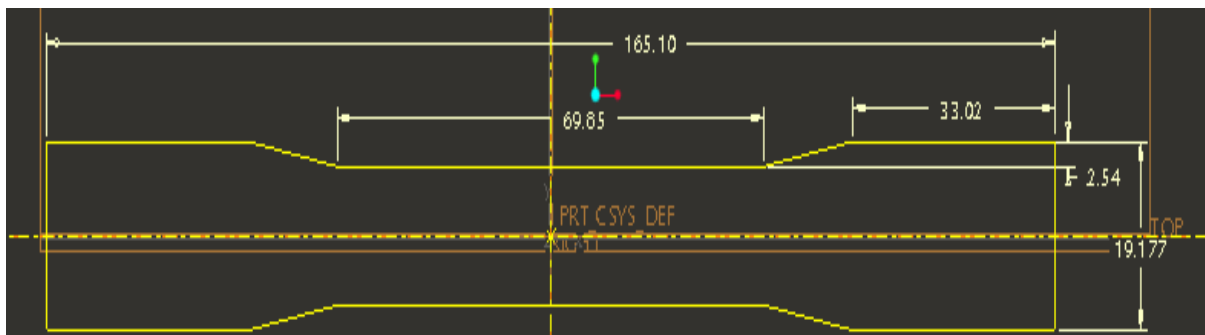


Figure 43. Dog bone sample layout (units mm).



Figure 44. Photograph of creep testing apparatus.

The creep test measures the amount of elongation that occurs as a function of time when a constant load is applied. When searching for engineering materials, it is important that the creep rate remains low as this means that the materials are not “growing” over time. This helps keep all structures safe for years to come when they consistently under load. Measuring creep is thus important because as a material is exposed to temperatures warmer than room temperature, it will begin to “grow.” In this study, creep was measured because utensils are exposed to temperatures of 100°C or greater. By measuring creep, one can see how much a material can grow and permanently deform after constant loading and temperature change.

The dogbone samples were then placed in the creep testing apparatus. Measurements were taken once the dogbone was clamped tightly in the vise jaws. After the test specimen was secure, a strain gauge was placed in the center of the dogbone, and the software was turned on. Measurements for creep were taken initially every few minutes and then every few hours up to 1,000 hours using the software on the Instron machine.

CHAPTER 3. RESULTS and DISCUSSION

3.1 Forks

As previously reported, Table 5 details the maximum allowable amount of deflection specified by the GSA for utensils. In addition, Table 6 details the companies that supplied utensils made from PLA (biobased) and conventional feed stocks, as well the amount of biobased content for each utensil. The numbers in Table 6 were obtained by sending a sample from each biobased brand of PLA utensil to Beta Analytic in Miami, Florida, where it was tested for biobased content according to ASTM D6866. Note that company names have been hidden; the companies are designated by letters only to ensure confidential information is not disclosed. It is also important to note that all of the tested biobased utensils consisted of biobased plastic. The assumption was made that additives, such as heat stabilizers and plasticers, made up the remaining percentages, although this cannot be proven because utensil manufacturers did not want to disclose their chemical formulas, which are confidential and proprietary. In this case, the companies were testing using FEA.

Table 5. *GSA accepted deflection levels.*

Utensil Type	Maximum Deflection (mm)
Fork	22.2
Knife	38.1
Spoons, tea	25.4

Table 6. *Resin type and relative biobased content.*

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

^aNot applicable due to utensils not being made from biobased resin.

Thirteen of the thirteen biobased forks met the flexibility standard set by the CID, as did conventional forks, while six out of six petrochemical companies met the flexibility standard. Biobased forks also had a low amount of deflection compared to the other forks tested.

To statistically determine if the utensil mass (g) affected the amount of deflection, a correlation was established between utensils mass and deflection, as shown in Figure 45.

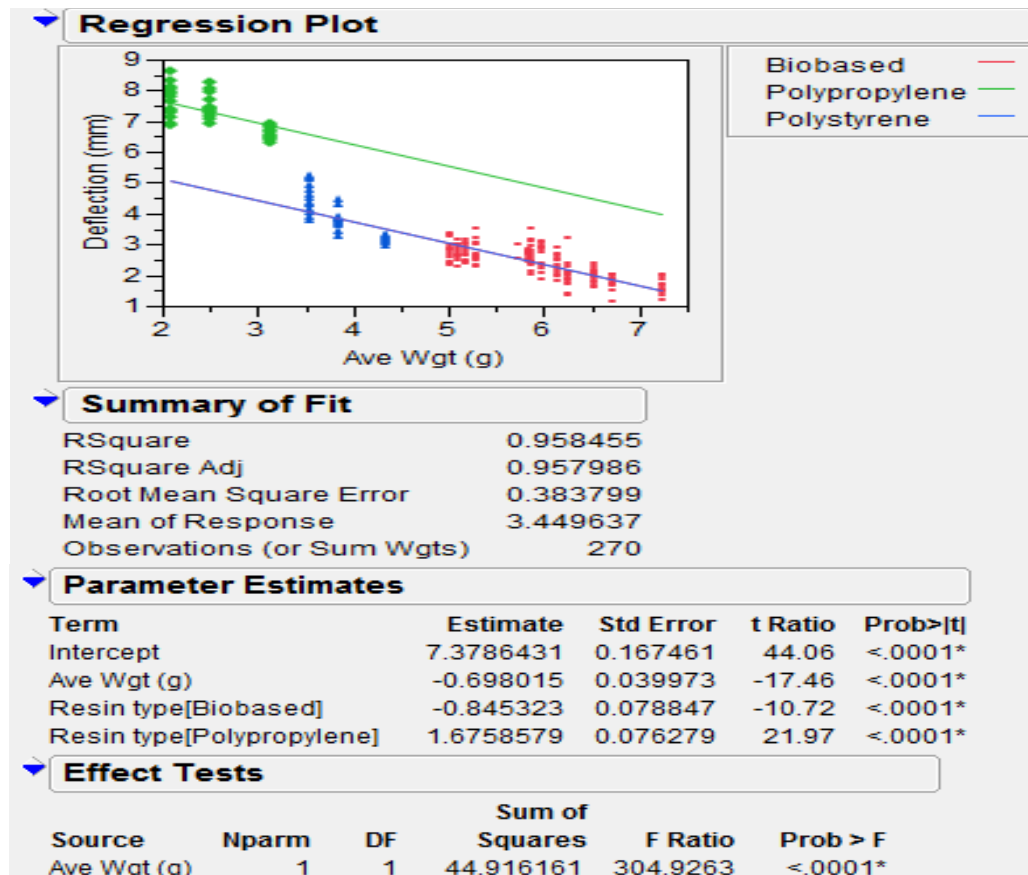


Figure 45. Fork R^2 value comparing fork mass (g) to deflection for all three resin types calculated together.

The overall fit of the model is very good, with an R^2 value of 0.958. To determine this value, all three resin types were calculated together. In Figure 45, only two lines show the slope because the slope of the data for the biobased and polystyrene resins is the same. Each specific resin type has its own slope line in Figure 45. For all three resins, this indicates that approximately 96% of the variation in deflection can be explained by the linear relationship with average weight for the three types of forks. From the plot, polypropylene is significantly different from both polystyrene and biobased resins; polystyrene and biobased

resins are similar. Further, to prove that deflection has a strong correlation to the overall weight of the utensil, Table 8 shows a “Prob > F” value. The figure confirms the strong correlation because the value is close to zero. After calculating all three resins, an F value of .0001 was obtained. To further support this theory statistically, an ANOVA table was constructed (see Figure 46).

Response Deflection (mm)				
Summary of Fit				
RSquare			0.958455	
RSquare Adj			0.957986	
Root Mean Square Error			0.383799	
Mean of Response			3.449637	
Observations (or Sum Wgts)			270	
Analysis of Variance				
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	903.93975	301.313	2045.552
Error	266	39.18226	0.147	Prob > F
C. Total	269	943.12200		<.0001*

Figure 46. Fork R^2 ANOVA calculation.

As Figure 46 shows, the F value remains statistically significant. Typically, the closer the value is to zero, the stronger the correlation between the two variables (weight (g) /deflection). In this case, forks have an F value of .0001.

If the specific compliance (deflection/mass) of the three resin types is estimated by approximating the center of each population, polystyrene, polypropylene, and biobased resins are 4, 1, and 0.5 (mm/g) respectively. More specifically, the typical deflection for

polypropylene was 8 mm, with a typical mass of 2 g, resulting in a specific compliance of 4 (mm/g). This suggests that the biobased forks were the most compliant on a mass basis or, in other words, the stiffest on a mass basis.

The previous calculations were performed a second time to statistically determine if a correlation existed between utensil mass (g) and the amount of deflection, as shown in Figure 47. Company G (89% biobased content) was excluded from the calculation. To determine which companies were outliers, anything that had a biobased percentage substantially larger (20% plus) than the other companies tested or was discarded. After removing these companies from the calculation, the R^2 value decreased from 0.958 to 0.946 because the deflections of the companies that were removed were closely positioned near the slope of the data. Removing those companies decreased the sample size, which therefore decreased the R^2 value.

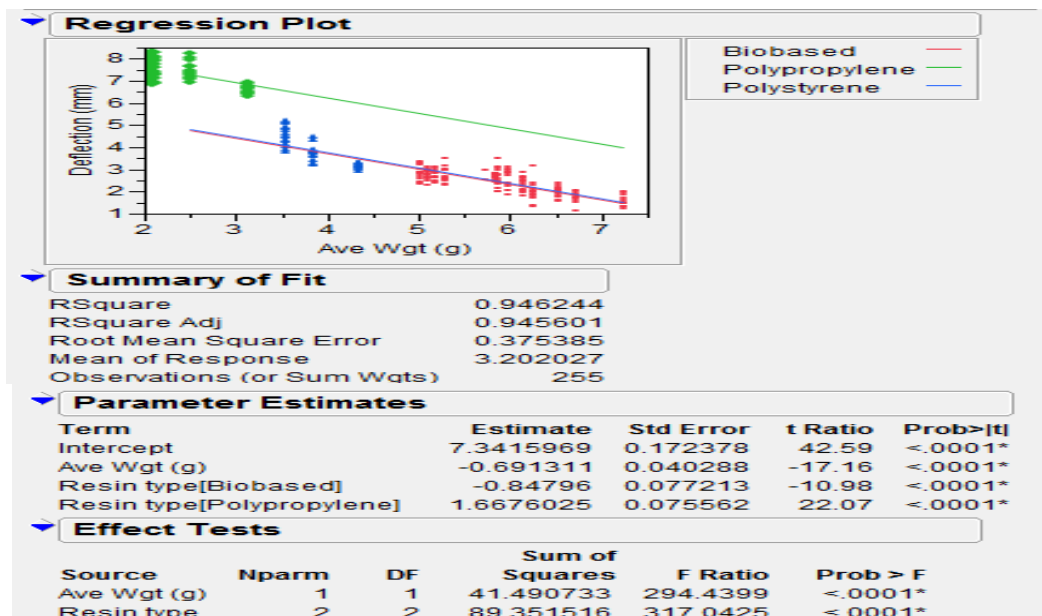


Figure 47. Fork R^2 value comparing fork mass (g) to deflection for all three resin types calculated together with outliers removed.

To support this correlation further, an ANOVA table as must be used to analyze the data (see Figure 48).

Response Deflection (mm)				
Summary of Fit				
RSquare				0.946244
RSquare Adj				0.945601
Root Mean Square Error				0.375385
Mean of Response				3.202027
Observations (or Sum Wgts)				255
Analysis of Variance				
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	622.59151	207.531	1472.745
Error	251	35.36944	0.141	Prob > F
C. Total	254	657.96094		<.0001*

Figure 48. Fork R^2 ANOVA calculation with outliers removed.

As Figure 48 shows, the F value remains statistically significant even with the outliers removed. Again, typically, the closer the value is to zero, the stronger the correlation between the two variables (weight (g) /deflection). In this case, with the fork outliers removed, an F value of .0001 is still calculated.

Figure 49 shows deflection as a function of mass (weight) and the relative number of ribs incorporated in the utensil design for the various resins. The number of ribs that the utensils had was broken into three categories, a) no ribs, b) medium number of ribs, and c) high number of ribs. The ribs were counted and placed into a respective category. For example, if the utensil had one rib on the outside profile (outside) of the fork and had one rib down the center of the fork handle, this fell into the medium number of ribs category. In order to be classified as having 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 did not matter; all the fork had to have was a rib feature.

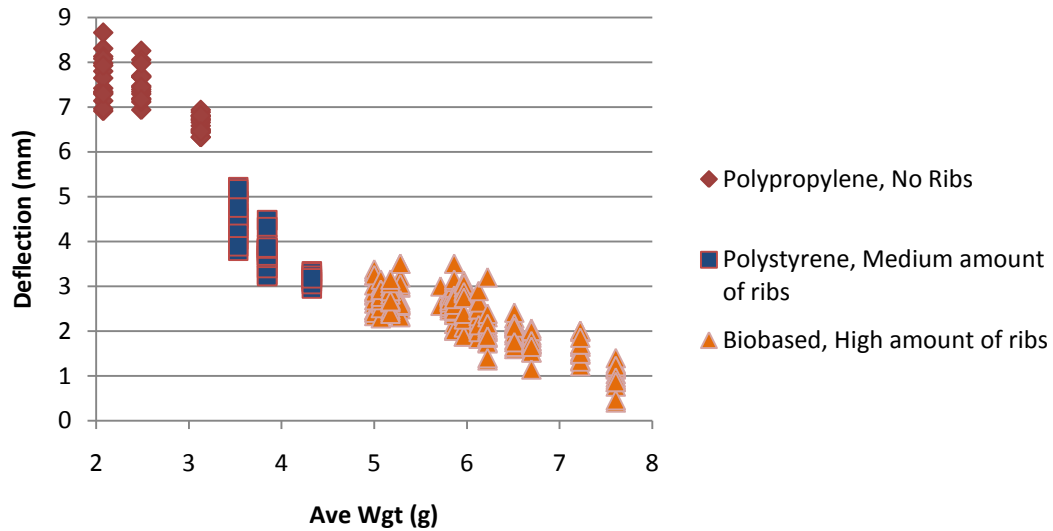


Figure 49. Fork deflection as a function of utensil mass (weight) as indicated by the number of ribs that each utensil contained.

As can be seen from Figure 49, the deflection is inversely proportional to fork mass and the number of ribs incorporated in the design. This is expected, as stiffness increases with cross-sectional area, which is proportional to the mass, as well a moment of inertia that increases with rib stiffeners. The table also shows that the polypropylene utensils tested did not contain ribs, while polystyrene contained a medium number and biobased (PLA) both contained a high number of ribs.

The statistical analysis detailed in Figure 50 correlates the biobased contents effect on deflection of the forks.

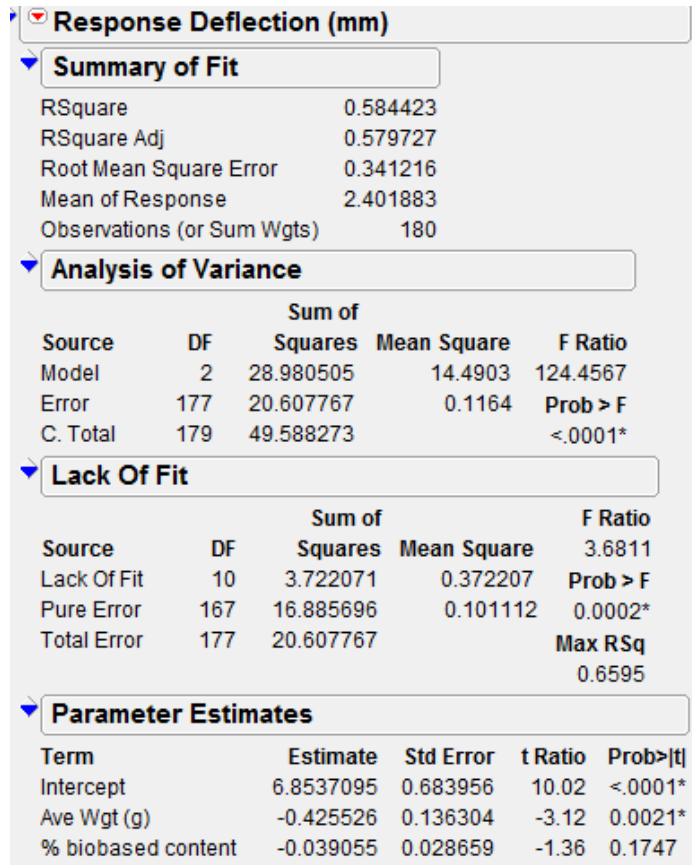


Figure 50. Amount of biobased content as a function of the deflection based on a normalized mass (weight) of the fork.

The model is statistically significant with an R^2 of 0.59, suggesting a significant amount of variation within the sampled population. In order to determine the R^2 value, all three resin types were calculated together. The deflection is significantly related to the mass/average weight, but the deflection is not significantly related to biobased content if the average weight of the product is removed from the model. This was done by not selecting the weight in that statistical software (JMP) and only using the biobased content percent and the deflection to calculate the R^2 value.

Another statistical analysis called the tolerance interval method was used to help answer the questions, what is the greatest amount of deflection in such that one is 95% confident that 99% of the deflection values will be less than the calculated upper tolerance limit? In addition, what is the lowest deflection value in such that one is 95% confident that 99% of the deflection values will be greater than the calculated lowest tolerance limit? The tolerance interval table indicates that if an individual were to place a 4.44 N load on the fork, 99% of the time the deflection values will fall within the range given in Table 7.

Table 7. Fork lower and upper tolerance intervals.

Company	Mean (mm)	Variance (mm)	Lower Deflection Value	Upper Deflection Value
A	2.8	0.00	2.0	3.6
B	2.8	0.00	1.6	4.1
C	1.6	0.00	0.8	2.5
D	2.0	0.00	1.2	2.8
E	2.8	0.00	1.9	3.6
F	2.0	0.01	0.5	3.6
G	0.9	0.00	0.3	1.5
H	2.4	0.00	1.3	3.5
I	2.6	0.01	1.1	4.1
J	3.8	0.00	3.4	4.1
K	1.7	0.00	0.9	2.5
L	2.6	0.01	1.1	4.1
M	7.7	0.01	5.8	9.5
N	3.2	0.00	2.8	3.5
O	2.7	0.00	2.3	3.1
P	7.5	0.02	6.2	8.8
Q	6.6	0.00	5.9	7.3
R	2.8	0.01	1.5	4.2
S	4.6	0.01	2.9	6.2

*95% confidence interval

Lastly, a confidence interval was used to determine what portion of the population (percentage) of the forks tested would deflect greater than 22.2 mm, as seen in Table 8. The confidence interval table helps give one an idea of what would happen if they picked up “Company X’s” fork and placed a 4.44 N load on it. They could expect a deflection value of somewhere in between the upper and lower confidence intervals. As expected, none of the types of forks failed. It is seen that the proportion that would exceed 22.2 mm of deflection (the maximum allowable) is zero for all types of forks.

Table 8. Amount of forks that deflect greater than GSA deflection acceptance level.

Company	Mean (mm) ^b	Variance (mm) ^c	Proportion (%) ^d
A	2.8	0.00	0.0
B	2.8	0.01	0.0
C	1.6	0.00	0.0
D	2.0	0.00	0.0
E	2.8	0.00	0.0
F	2.0	0.01	0.0
G	1.0	0.00	0.0
H	2.4	0.00	0.0
I	2.6	0.01	0.0
J	3.8	0.00	0.0
K	1.7	0.00	0.0
L	2.6	0.01	0.0
M	7.7	0.01	0.0
N	3.2	0.00	0.0
O	2.7	0.00	0.0
P	7.5	0.01	0.0
Q	6.6	0.00	0.0
R	2.8	0.01	0.0
S	4.5	0.01	0.0

*95% confidence interval^e

^bAverage deflection for each of the 15 companies' tested utensils.

^cSignifies how far the data are from the mean.

^dIndicates at the 95% confidence level, the percentage of that company's utensil that fails.

^eThe range around a measurement that conveys how precise the measurement is.

3.2 Knife

Biobased knives did not meet the flexibility standard set in the CID as six out of 13 companies tested showed significantly high failure rates. Those companies showed that between 25% and 100% of the biobased knives would not meet flexibility requirements, although biobased knives performed better than conventional knives that had no companies meet test specifications. All six conventional companies showed that 99% to 100% of the knives would fail flexibility. Biobased knives also had some of the lowest deflection amounts of all the knives tested, while conventional knives had some of the highest amounts of deflection.

In order to statistically determine if the utensil mass (g) affected the amount of deflection, a correlation was established between utensils mass and deflection, as seen in Figure 51.

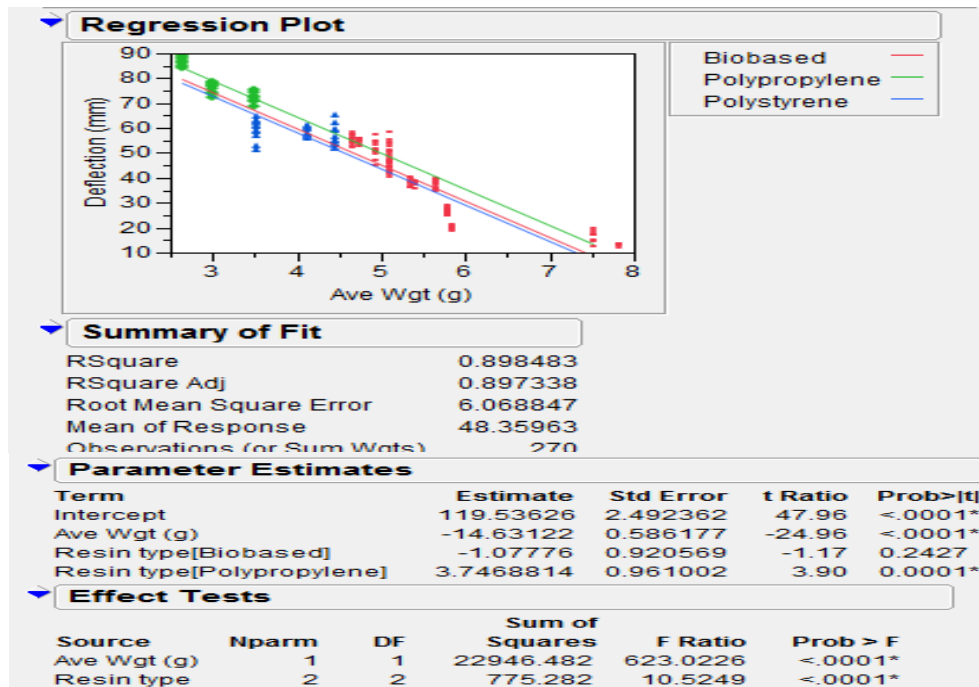


Figure 51. Knife R^2 value comparing knife mass (g) to deflection for all three resin types calculated together.

The overall fit of the model is very good, with an R^2 value of 0.898. In order to determine this value, all three resin types were calculated together. Each specific resin type has its own slope line in Figure 51 to show what the slope of the various utensils tested would be if they were calculated individually. For all three resins tested, this indicates that about 90% of the variation in deflection can be explained by the linear relationship with average weight for the three types of knives. From the plot, polypropylene is significantly different from both polystyrene and biobased, while polystyrene and biobased are similar. In addition, to help prove that deflection has a strong correlation to the overall weight of the utensil, Figure 51 shows a “Prob > F” value. The figure confirms the strong correlation

because the value is close to zero. After calculating all three resins together, an F value of .0001 was obtained. To further support this theory statistically, an ANOVA table was constructed (see Figure 52).

Response Deflection (mm)

Summary of Fit

RSquare	0.898483
RSquare Adj	0.897338
Root Mean Square Error	6.068847
Mean of Response	48.35963
Observations (or Sum Wgts)	270

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	86708.950	28903.0	784.7482
Error	266	9797.019	36.8	Prob > F
C. Total	269	96505.969		<.0001*

Figure 52. Knife R^2 ANOVA calculation.

As Figure 52 shows, the F value remains statistically significant. Again, typically, the closer the value is to zero, the stronger the correlation between the two variables (weight (g) /deflection). In this case, knives have an F value of .0001. If the specific compliance (deflection/mass) of the three resin types is estimated by approximating the center of each population, polystyrene, polypropylene, and biobased are 25, 15, and 10 (mm/g) respectively. More specifically, the typical deflection for polypropylene was 75 mm, with a typical mass of 3 g, resulting in a specific compliance of 25 (mm/g). This suggests that the biobased knives were the most compliant on a mass basis or, in other words, the stiffest on a mass basis.

The previous calculations were performed a second time to statistically determine if a correlation existed between utensil mass (g) and the amount of deflection, as seen in Table 16. Company G (89% biobased content) was excluded from the calculation. To determine which companies were outliers, anything that had a biobased percentage substantially larger (20% plus) than the other companies tested was discarded. After removing these companies from the calculation, the R^2 value decreased from 0.898 to 0.867 because the deflections of the companies that were removed were closely positioned near the slope (regression line) of the data. Removing those companies decreased the sample size, which therefore decreased the R^2 value. This can be seen in Figure 53 because several values that fell around the slope were removed.

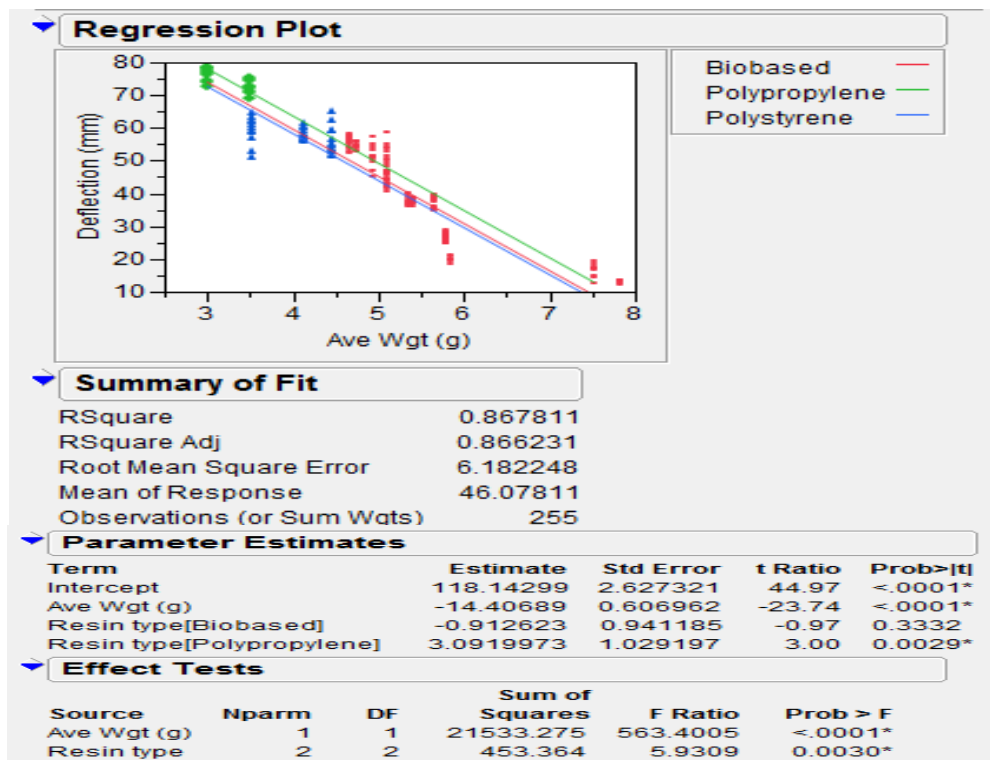


Figure 53. Knife R^2 value comparing knives mass (g) to deflection for all three resin types calculated together with outliers removed.

To support this correlation further, an ANOVA Table must be used to analyze the data (see Figure 54).

Response Deflection (mm)				
Summary of Fit				
RSquare			0.867811	
RSquare Adj			0.866231	
Root Mean Square Error			6.182248	
Mean of Response			46.07811	
Observations (or Sum Wgts)			255	
Analysis of Variance				
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	62979.110	20993.0	549.2656
Error	251	9593.268	38.2	Prob > F
C. Total	254	72572.378		<.0001*

Figure 54. Knife R² ANOVA calculation with outliers removed.

As Figure 54 shows, the F value remains statistically significant even with the outliers removed. Typically, the closer the value is to zero, the stronger the correlation between the two variables (weight (g) / deflection). In this case, with knives outliers removed, an F value of .0001 is still calculated.

Figure 55 shows deflection as a function of mass (weight) and the relative number of ribs incorporated in the utensil design for the various resins. The number of ribs that the utensils had was broken into three categories, a) no ribs, b) medium number of ribs, and c) high number of ribs. The ribs were counted and placed into a respective category. For example, if the utensil had one rib on the outside profile (outside) of the knife, this fell into the medium number of ribs category. In order to be classified as having a high number of ribs, the knives had to contain both a rib around the profile (outside) of the knife and on the

side of the handle. The height or width of the rib did not matter; all the knife had to have was a shape resembling a rib feature.

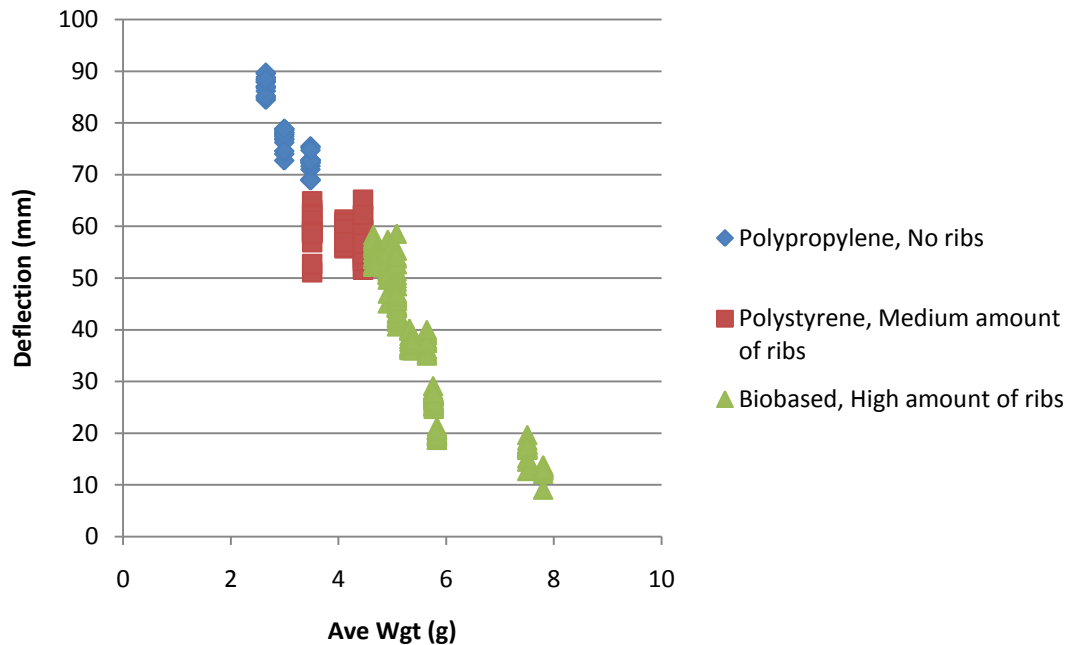


Figure 55. Knife deflection as a function of utensil mass (weight) indicated by the amount of ribs that each utensil contained.

As can be seen from Figure 55, the deflection is inversely proportional to knife mass and the number of ribs incorporated in the design. This is expected, as stiffness increases with cross-sectional area, which is proportional to the mass, as well a moment of inertia that increases with rib stiffeners. The table also shows that the polypropylene utensils tested did not contain ribs, while polystyrene contained a medium number and biobased (PLA) both contained a high number of ribs.

The statistical analysis detailed in Figure 56 correlates the biobased contents effect on deflection of the knives.

Response Deflection (mm)

Summary of Fit

RSquare	0.918479
RSquare Adj	0.917558
Root Mean Square Error	3.736312
Mean of Response	38.36024
Observations (or Sum Wgts)	180

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	2	27839.385	13919.7	997.1106
Error	177	2470.925	14.0	Prob > F
C. Total	179	30310.310		<.0001*

Lack Of Fit

Source	DF	Sum of Squares	Mean Square	F Ratio
Lack Of Fit	9	1803.4447	200.383	50.4349
Pure Error	168	667.4804	3.973	Prob > F
Total Error	177	2470.9251		Max RSq
				0.9780

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob> t
Intercept	218.47519	5.29542	41.26	<.0001*
Ave Wgt (g)	-3.421531	0.71288	-4.80	<.0001*
% biobased content	-3.26028	0.164557	-19.81	<.0001*

Figure 56. Amount of biobased content as a function of the deflection based on a normalized mass (weight) of the knives.

The model is statistically significant, with an R^2 of 0.92 suggesting a small amount of variation within the sampled population. To determine the R^2 value, all three resin types were still calculated together. The deflection is significantly related to the mass/average weight, but the deflection is not significantly related to biobased content if the average weight of the product is removed from the model. This was done by not selecting the weight in that statistical software (JMP) and only using the biobased content percent and the deflection to calculate the R^2 value.

Another statistical analysis called the tolerance interval method was used to help answer the questions, what is the greatest amount of deflection in such that one is 95% confident that 99% of the deflection values will be less than the calculated the upper

tolerance limit? In addition, what is the lowest deflection value in such that one is 95% confident that 99% of the deflection values will be greater than the calculated lowest tolerance limit? The tolerance interval table indicates that if an individual were to place a 4.44 N load on the knives, 99% of the time the deflection values will fall within the range given in Table 9.

Table 9. *Knife lower and upper tolerance intervals.*

Company	Mean (mm)	Variance (mm)	Lower Tolerance Interval	Upper Tolerance Interval
A	51.1	0.70	50.1	58.9
B	55.2	0.16	48.1	62.2
C	16.8	0.11	10.9	22.9
D	26.1	0.03	22.9	29.3
E	54.5	0.06	36.2	65.9
F	27.4	0.04	24.1	30.8
G	12.9	0.05	10.1	15.9
H	37.6	0.09	32.4	42.9
I	38.1	0.09	32.7	43.6
J	58.1	0.13	51.7	64.6
K	19.8	0.02	17.3	22.6
L	37.8	0.03	35.0	40.7
M	87.1	0.13	81.1	93.2
N	56.6	0.68	41.8	71.1
O	44.2	0.19	36.4	52.0
P	76.9	0.14	70.3	83.7
Q	72.2	0.17	64.8	79.6
R	51.3	0.35	40.8	61.8
S	59.2	5.19	46.4	66.7

*95% confidence interval

Lastly, a confidence interval was used to determine what portion of the population (percentage) of the knives tested would deflect greater than 38.1 mm, as seen in Table 10.

The confidence interval table helps give one an idea of what would happen if they picked up “Company X’s” knife and placed a 4.44 N load on it. They could expect a deflection value of somewhere between the upper and lower confidence intervals. A large portion of both biobased and petrochemical knives did not meet test specifications, as the proportion that would exceed 38.1 mm of deflection (the maximum allowable) is 97% to 100% for the majority of knives.

Table 10. *Amount of knives that deflect greater than GSA deflection acceptance level.*

Company	Mean (mm)	Variance (mm)	Proportion (%)
A	51.1	0.70	0.97
B	55.2	0.16	0.99
C	16.8	0.11	0.00
D	26.1	0.03	0.00
E	54.5	0.06	0.99
F	27.4	0.03	0.00
G	12.9	0.05	0.00
H	37.6	0.09	0.27
I	38.1	0.09	0.33
J	58.2	0.13	0.99
K	19.8	0.02	0.00
L	37.8	0.03	0.27
M	87.1	0.12	1.00
N	56.6	0.68	0.99
O	44.2	0.19	0.98
P	76.9	0.14	1.00
Q	72.2	0.17	1.00
R	51.3	0.35	0.97
S	59.2	5.19	0.99

*95% confidence interval

3.3 Spoons

Thirteen out of thirteen biobased spoon companies met the flexibility standard set by the CID. Of the six conventional companies, four had spoons that did not pass; the remaining two met specifications.

Biobased spoons performed better than conventional spoons. Conventional spoons had two companies meet test specifications. All four conventional companies that did not meet test specifications showed that 93% to 100% of the spoons tested would fail flexibility. Biobased spoons also had some of the lowest deflection amounts of all the spoons tested, while conventional spoons had some of the highest amounts of deflection.

In order to statistically determine if the utensil mass affected the amount of deflection, a correlation was established between utensil mass (g) and deflection, as seen in Figure 57.

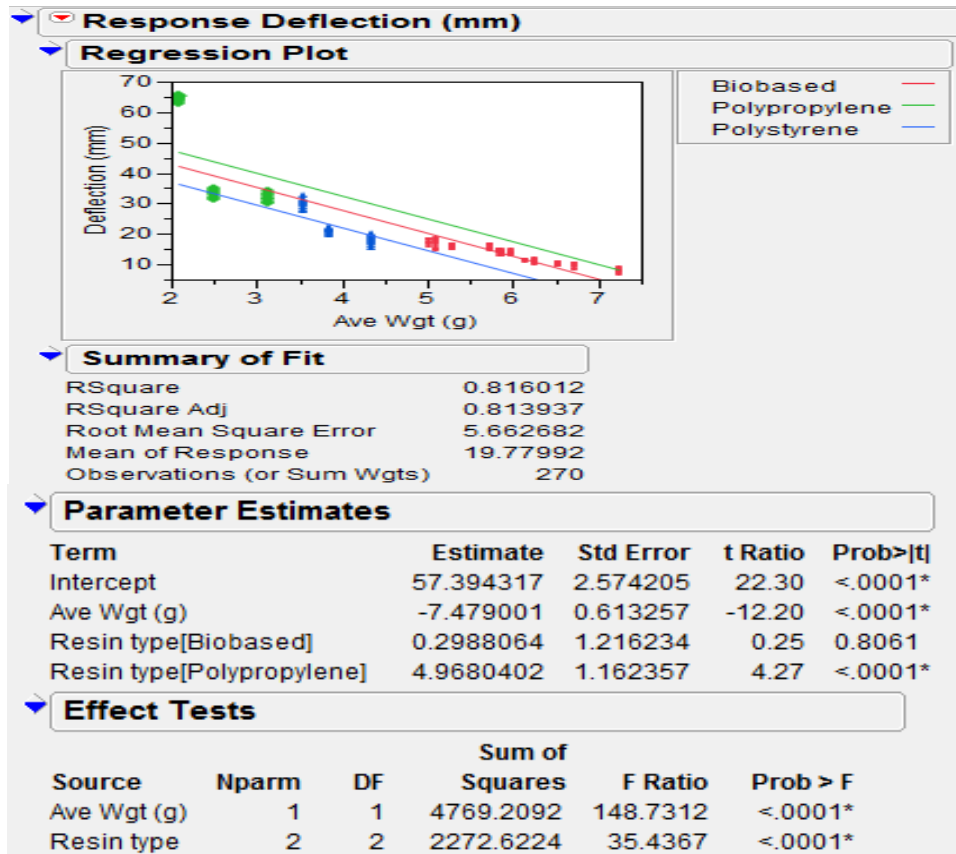


Figure 57. Spoon R^2 value comparing spoon mass (g) to deflection for all three resin types calculated together.

The overall fit of the model is very good, with an R^2 value of 0.816. In order to determine this value, all three resin types were calculated together. Each specific resin type has its own slope line in Figure 57 to show what the slope of the various utensils tested would be if calculated individually. For all three resins tested, this indicates that about 82% of the variation in deflection can be explained by the linear relationship with average weight for the three spoons. From the plot, polypropylene is significantly different from both polystyrene and biobased, while polystyrene and biobased are similar. In addition, to help prove that deflection has a strong correlation to the overall weight of the utensil, Figure 57

shows a “Prob > F” value. The table shows a strong correlation because the value is close to zero. After calculating all three resins together, an F value of .0001 was obtained. To further support this theory statistically, an ANOVA table was constructed (see Figure 58).

Response Deflection (mm)				
Summary of Fit				
RSquare		0.816012		
RSquare Adj		0.813937		
Root Mean Square Error		5.662682		
Mean of Response		19.77992		
Observations (or Sum Wgts)		270		
Analysis of Variance				
Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	37829.664	12609.9	393.2484
Error	266	8529.547	32.1	Prob > F
C. Total	269	46359.211		<.0001*

Figure 58. Spoon R² ANOVA calculation.

As Figure 58 shows, the F value remains statistically significant. Typically, the closer the value is to zero, the stronger the correlation between the two variables (weight (g) /deflection). In this case, knives have an F value of .0001.

If the specific compliance (deflection/mass) of the three resin types is estimated by approximating the center of each population, polystyrene, polypropylene, and biobased are 14, 6.25, and 2.5 (mm/g) respectively. More specifically, the mean deflection for polypropylene was 35 mm, with a mean mass of 2 g, resulting in a specific compliance of

6.25 (mm/g). This suggests that the biobased spoons were the most compliant on a mass basis or, in other words, the stiffest on a mass basis.

The previous calculations were performed a second time to statistically determine if a correlation existed between utensil mass and the amount of deflection, as shown in Figure 59. Company G (89% biobased content) was excluded from the calculation. To determine which companies were outliers, anything that had a biobased percentage that was substantially larger (20% plus) than the other companies tested was discarded. After removing these companies from the calculation, the R^2 value increased from 0.816 to 0.935 because the deflections of the companies that were removed were scattered all over (not close) the regression line of the data. Removing those companies decreased the sample size, which therefore increased the R^2 value. This can be seen in Figure 59 because several values that fell farther away from the slope were removed.

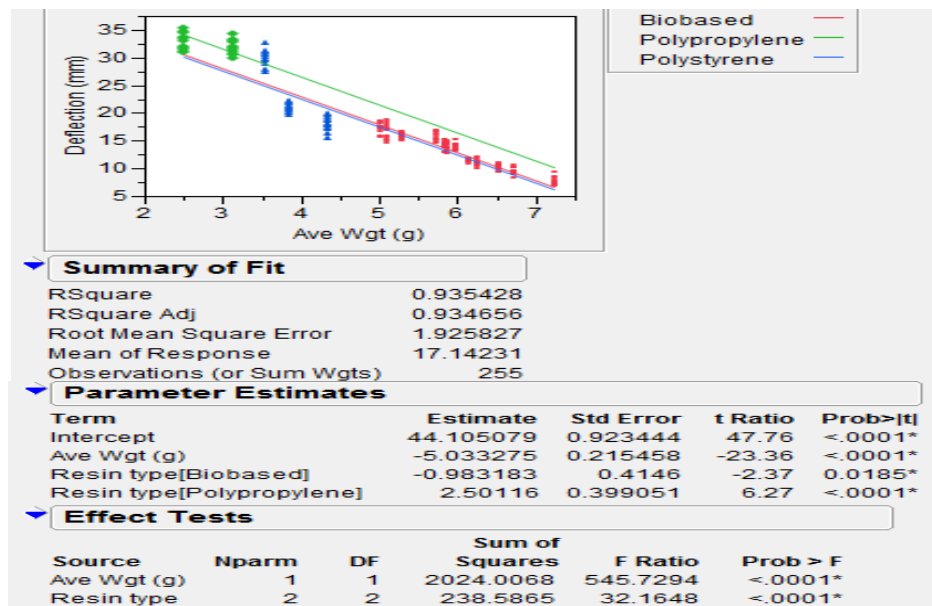


Figure 59. Spoon R^2 value comparing spoon mass (g) to deflection for all three resin types calculated together with outliers removed.

To support this correlation further, an ANOVA Table must be used to analyze the data (see Figure 60).

Response Deflection (mm)

Summary of Fit

RSquare	0.935428
RSquare Adj	0.934656
Root Mean Square Error	1.925827
Mean of Response	17.14231
Observations (or Sum Wgts)	255

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	3	13485.697	4495.23	1212.042
Error	251	930.911	3.71	Prob > F
C. Total	254	14416.609		<.0001*

Figure 60. Spoon R^2 ANOVA calculation with outliers removed.

As Figure 60 shows, the F value remains statistically significant, even with the outliers removed. Typically, the closer the value is to zero, the stronger the correlation between the two variables (weight (g) /deflection). In this case, with spoon outliers removed, an F value of .0001 is still calculated, but this time with an increased R^2 value.

Figure 61 shows deflection as a function of mass (weight) and the relative number of ribs incorporated in the utensil design for the various resins. The number of ribs that the utensils had was broken into three categories, a) no ribs, b) medium number of ribs, and c) high number of ribs. The ribs were counted and placed into a respective category. For

example, if the utensil had one rib on the outside profile (outside) of the spoon, it fell into the medium number of ribs category. In order to be classified as having a high number of ribs, the spoons had to contain both a rib around the profile (outside) of the spoon and in the middle of the handle. The height or width of the rib did not matter; all the spoon had to have was a shape resembling a rib feature.

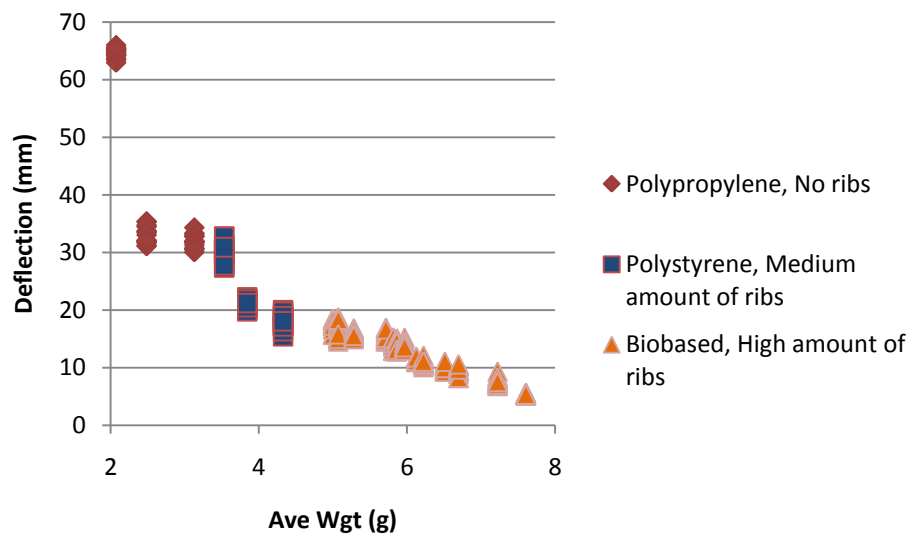


Figure 61. Spoon deflection as a function of utensil mass (weight) indicated by the amount of ribs that each utensil contained.

As can be seen from Figure 61, the deflection is inversely proportional to spoon mass and the number of ribs incorporated in the design. This is expected, as stiffness increases with cross-sectional area, which is proportional to the mass, as well a moment of inertia that increases with rib stiffeners. The table also shows that the polypropylene utensils tested did not contain ribs, while polystyrene contained a medium number and biobased (PLA) both contained a high number of ribs.

The statistical analysis detailed in Figure 62 correlates the biobased contents effect on deflection of the spoons.

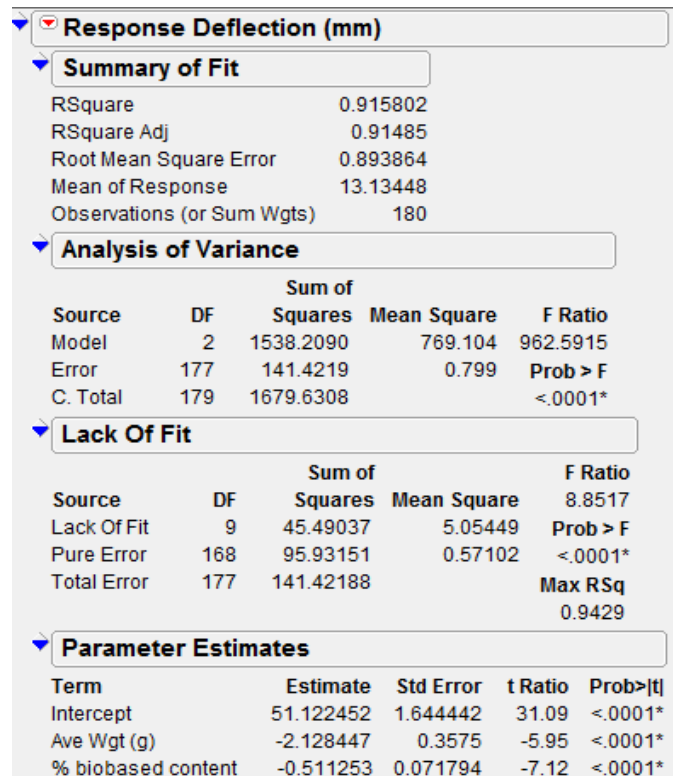


Figure 62. Amount of biobased content as a function of the deflection based on a normalized mass (weight) of the spoons.

The model is statistically significant with an R^2 of 0.92, suggesting a small amount of variation within the sampled population. In order to determine the R^2 value, all three resin types were calculated together. The deflection is significantly related to the mass/average weight, but the deflection is not significantly related to biobased content if the average weight of the product is removed from the model. This was done by not selecting the weight in that statistical software (JMP) and only using the biobased content percent and the deflection to calculate the R^2 value.

Another statistical analysis called the tolerance interval method was used to help answer the questions, What is the greatest amount of deflection in such that one is 95% confident that 99% of the deflection values will be less than the calculated the upper tolerance limit? In addition what is the lowest deflection value in such that one is 95% confident that 99% of the deflection values will be greater than the calculated lowest tolerance limit? The tolerance interval table indicates that if an individual were to place a 4.44 N load on the spoon, 99% of the time the deflection values will fall within the range given in Table 11.

Table 11. *Spoon lower and upper tolerance intervals.*

Company	Mean (mm)	Variance (mm)	Lower Tolerance Interval	Upper Tolerance Interval
A	16.5	0.08	11.6	21.4
B	17.6	0.03	14.4	20.7
C	7.7	0.02	5.3	10.1
D	10.1	0.01	8.2	12.0
E	15.6	0.03	12.8	18.5
F	10.9	0.01	9.0	12.9
G	5.4	0.00	4.1	6.3
H	11.5	0.00	10.5	12.5
I	14.1	0.02	11.6	16.7
J	21.0	0.02	18.5	23.5
K	9.6	0.02	6.9	12.3
L	13.8	0.01	11.7	15.9
M	64.6	0.03	61.6	67.6
N	17.9	0.06	13.5	22.5
O	14.2	0.02	11.7	16.8
P	33.0	0.08	27.9	38.2
Q	31.9	0.06	27.7	36.1
R	15.8	0.01	13.7	17.9
S	29.9	0.11	23.8	35.9

*95% confidence interval

Lastly, a confidence interval was used to determine what portion of the population (percentage) of the spoons tested would deflect greater than 25.4 mm, as seen in Table 12. The confidence interval table helps give one an idea of what would happen if they were to pick up “Company X’s” spoons and place a 4.44 N load on it. They could expect a deflection value of somewhere in between the upper and lower confidence intervals. As expected, a very small percentage of spoons failed. It is seen that the proportion that would exceed 25.4 mm of deflection (the maximum allowable) is zero for several of spoons and 93% to 100% for the remainder.

Table 12. *Relative amount of spoons that deflect greater than GSA deflection acceptance level.*

Company	Mean (mm)	Variance (mm)	Proportion (%)
A	16.5	0.08	0.00
B	17.6	0.03	0.00
C	7.7	0.02	0.00
D	10.1	0.01	0.00
E	15.6	0.03	0.00
F	10.9	0.01	0.00
G	5.4	0.00	0.00
H	11.4	0.00	0.00
I	14.1	0.02	0.00
J	21.0	0.02	0.00
K	9.6	0.02	0.00
L	13.8	0.01	0.00
M	64.6	0.03	1.00
N	17.9	0.06	0.00
O	14.2	0.02	0.00
P	33.0	0.08	0.99
Q	31.9	0.06	0.99
R	15.8	0.01	0.00
S	29.8	0.12	0.93

*95% confidence interval

3.4 Finite Element Analysis

Finite Element Analysis (FEA) models were used for selected biobased and conventional utensil types and validated with the data from the actual testing. As seen Figure 44, the predicted deflection based on FEA models was in good agreement with experimental measurements values. In addition, Figure 63 shows that the predicted and actual values are also in good agreement. Further, Figures 64 thru 75 show that the highest stress in each utensil is in the handle body of the utensils. This is in good agreement that with the experimental data that suggested support ribs in the handle greatly increase stiffness. Adding ribs reduces stress and the overall amount of deflection.

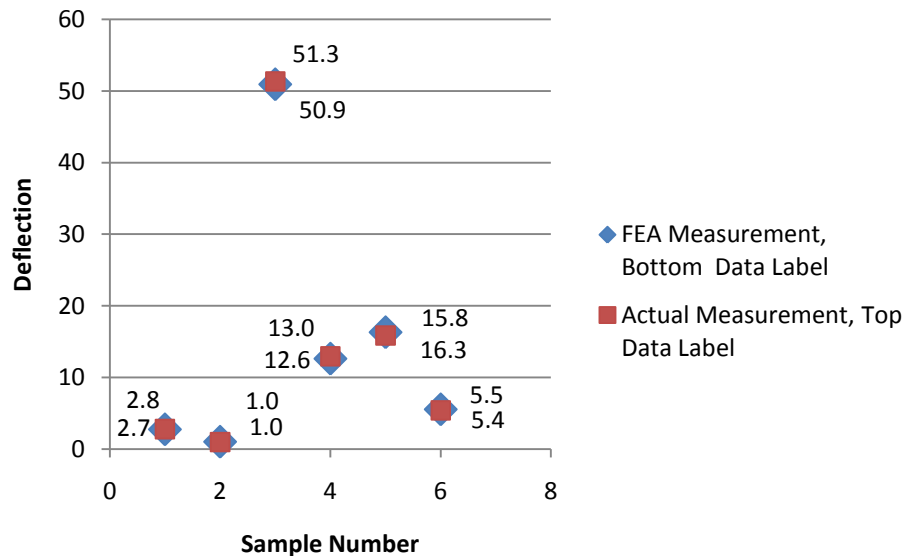


Figure 63. Deflection as a function of load for experimental and predicted values.

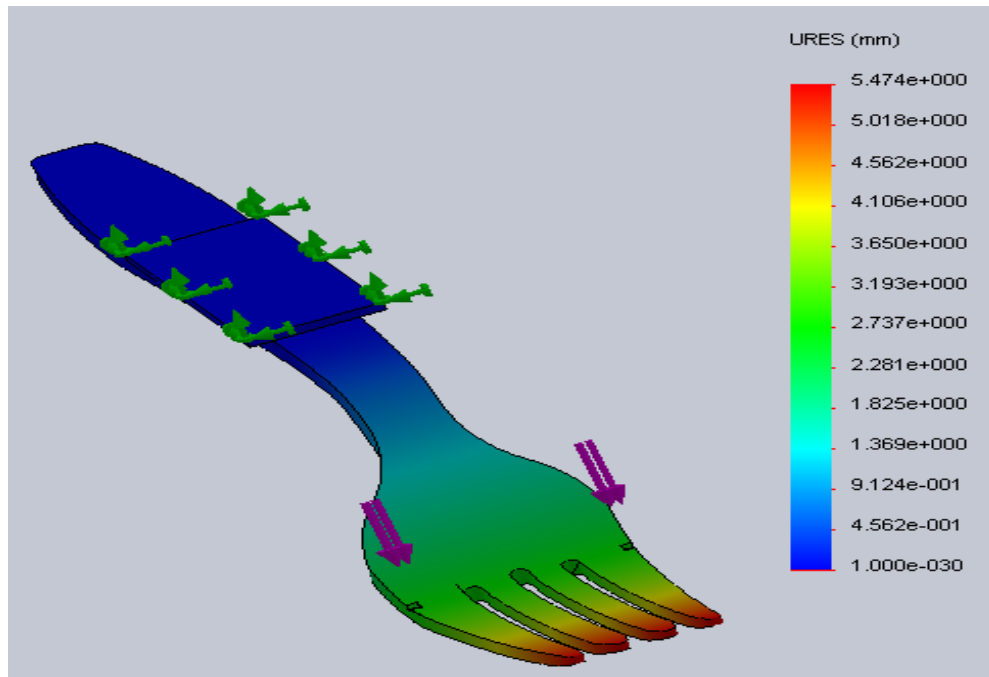


Figure 64. Premiearware FEA fork deflection results.

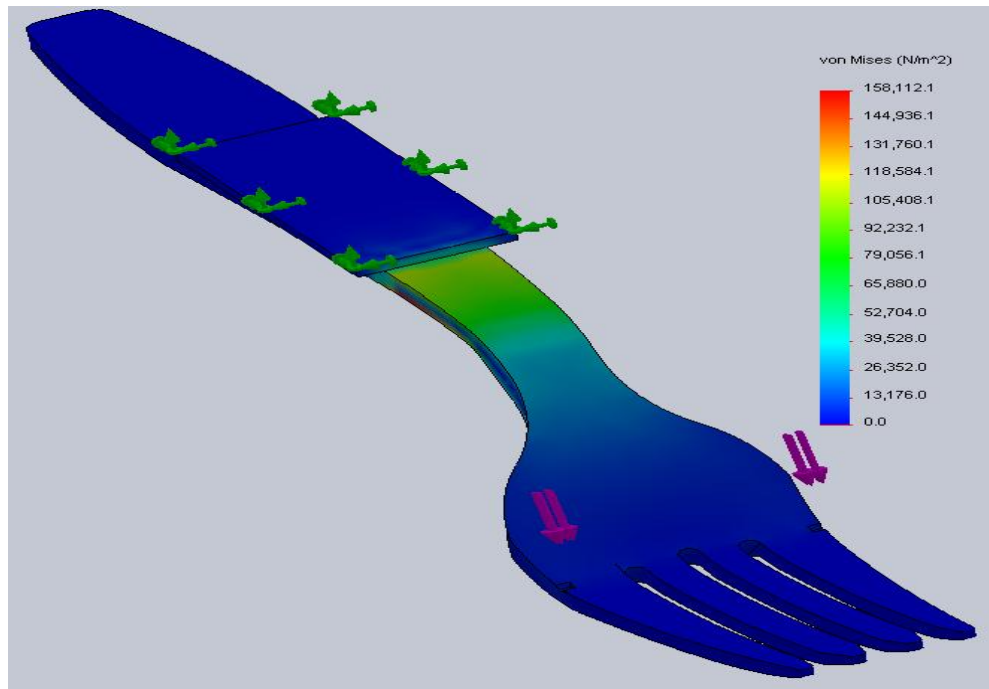


Figure 65. Premiearware fork stress analysis.

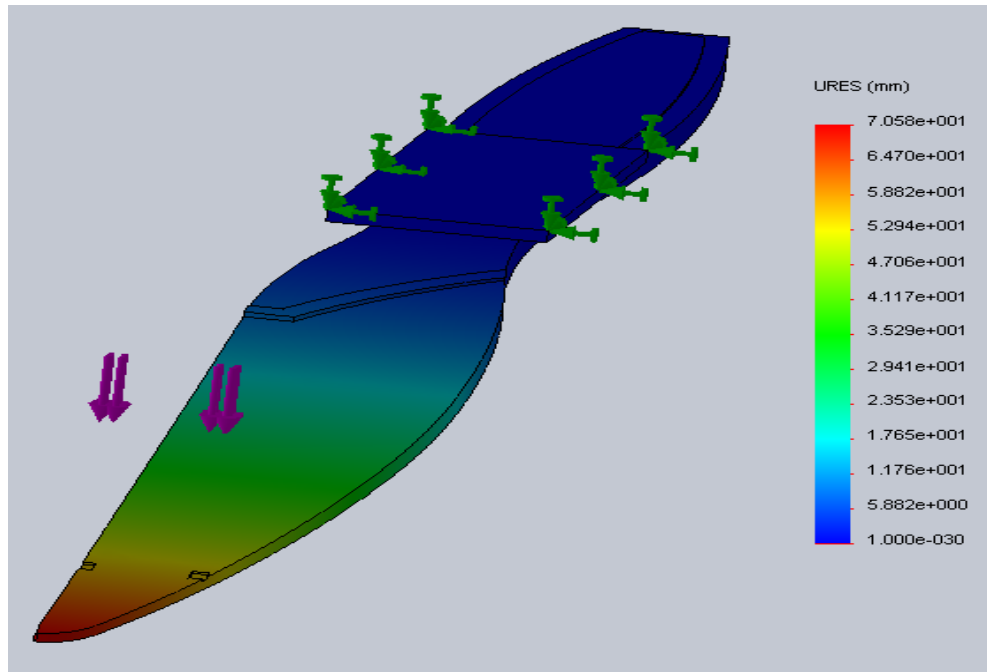


Figure 66. Premiarware FEA knife deflection results.

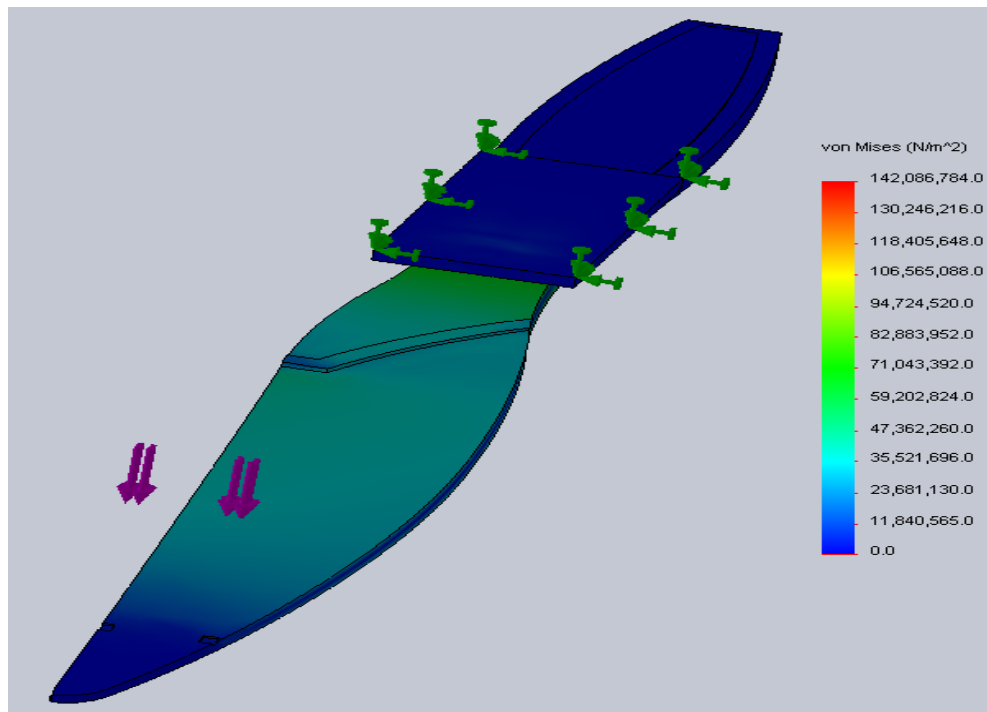


Figure 67. Premiarware knife stress analysis.

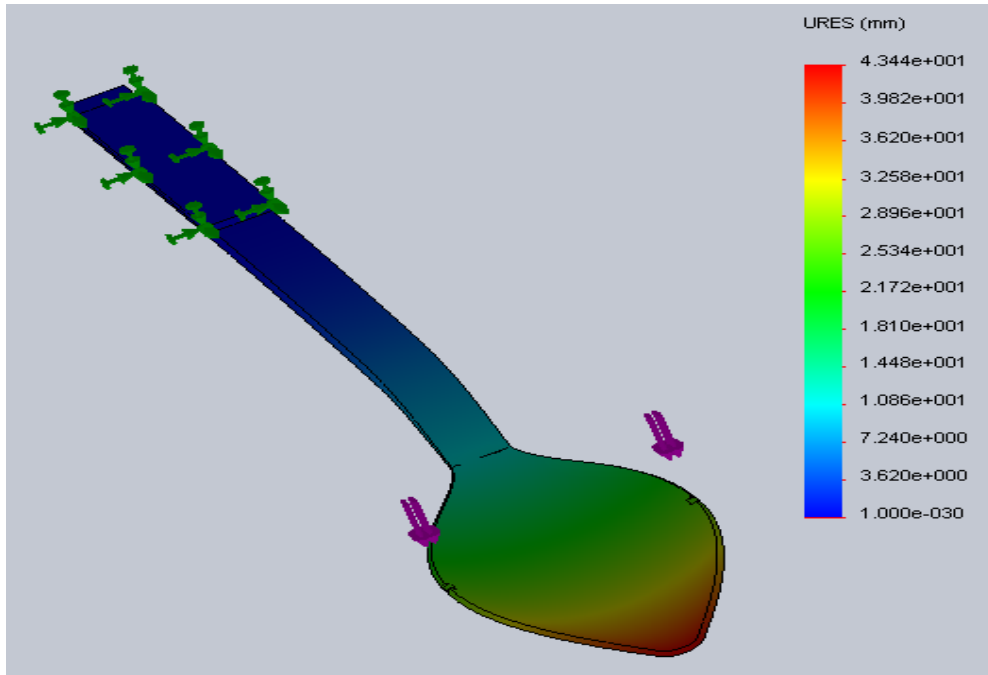


Figure 68. Premiearware FEA spoon deflection results.

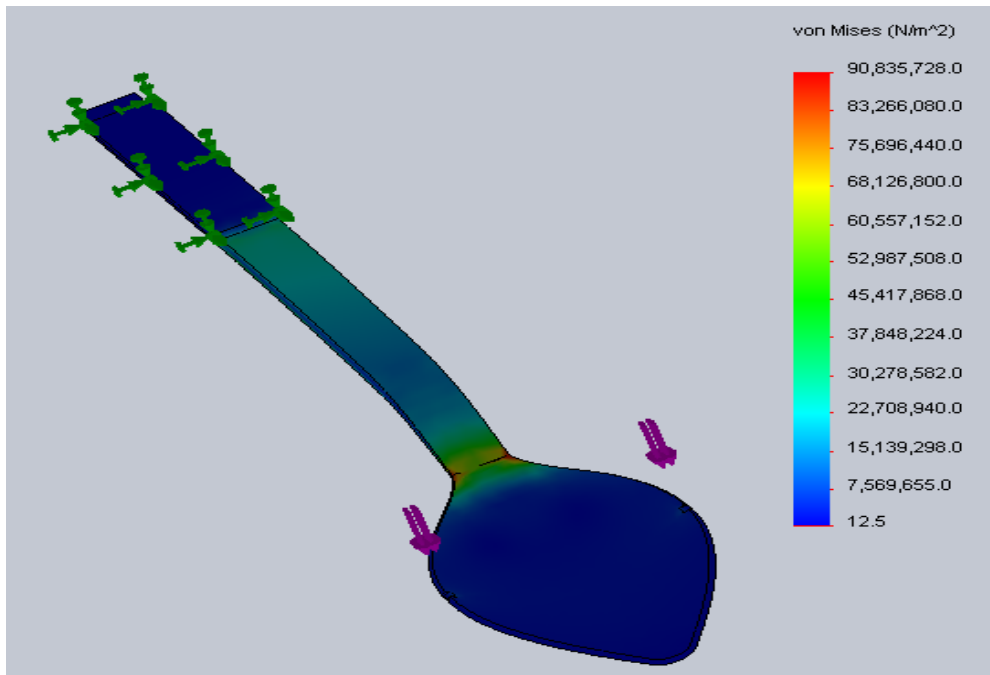


Figure 69. Premiearware spoon stress analysis.

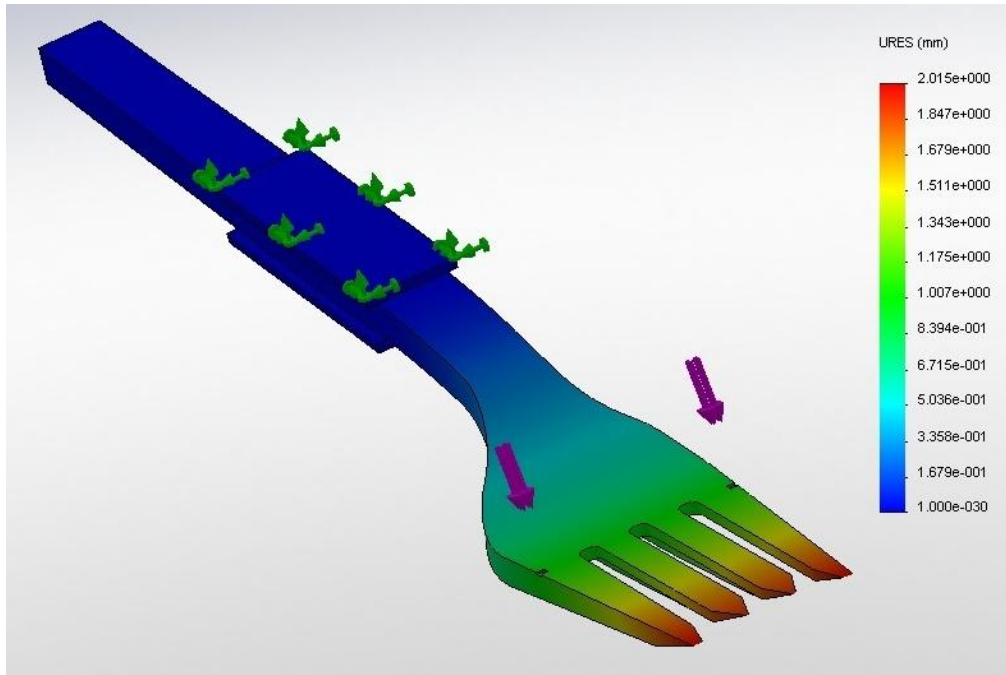


Figure 70. Eco-Products FEA fork deflection results.

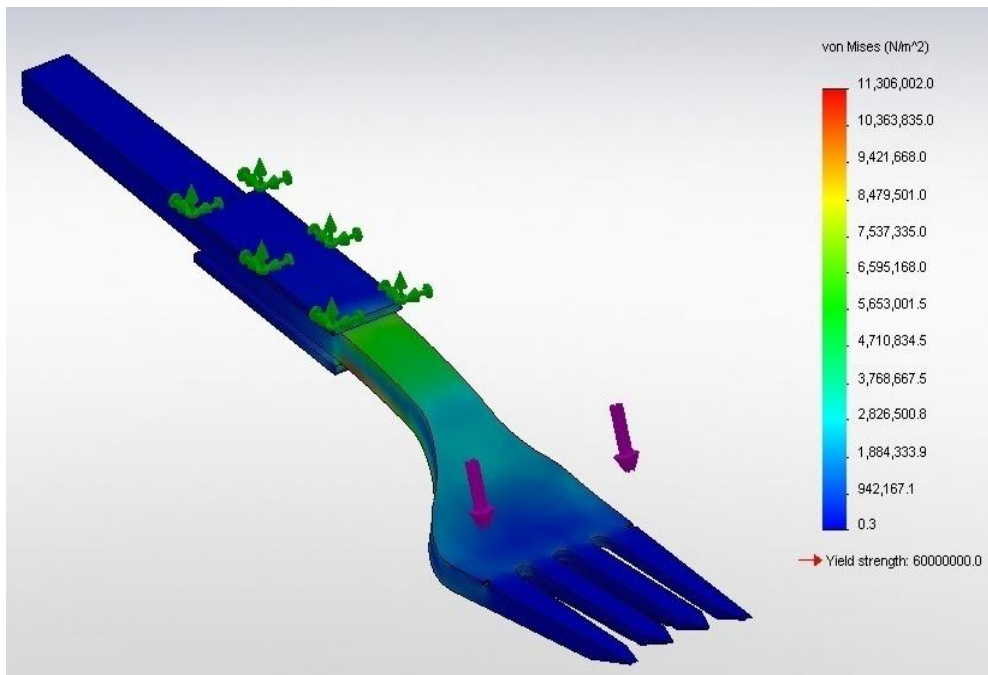


Figure 71. Eco-Products fork stress analysis.

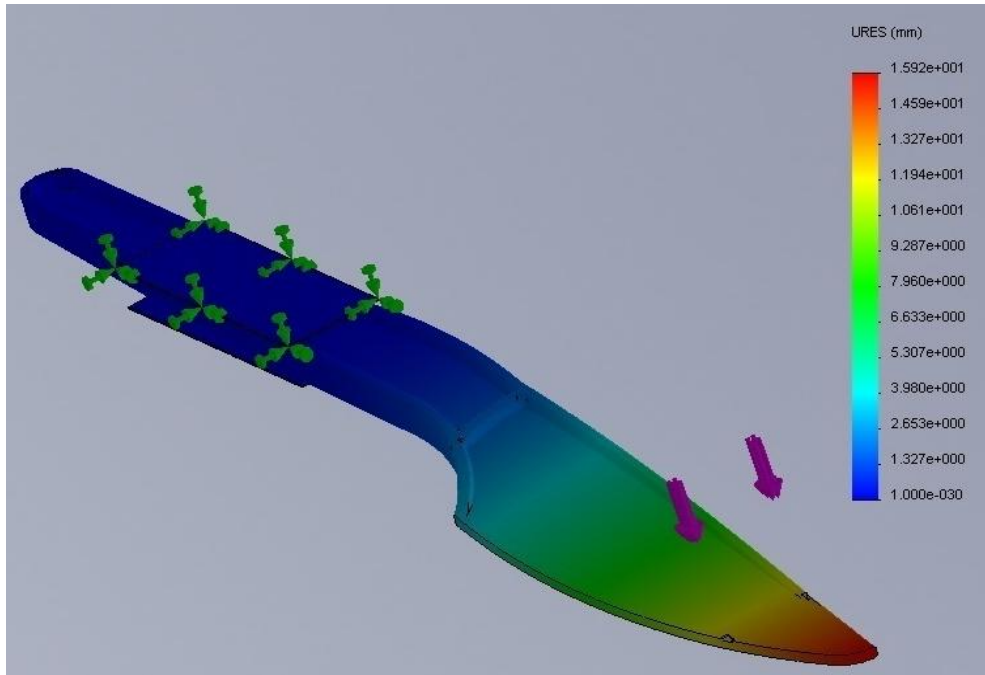


Figure 72. Eco-Products FEA knife deflection results.

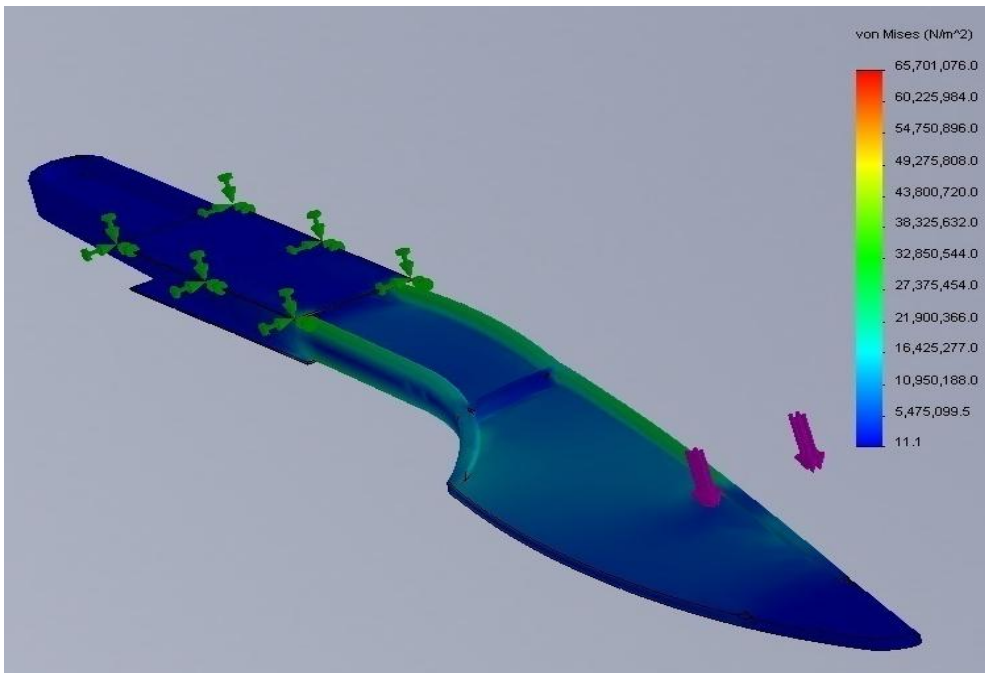


Figure 73. Eco-Products knife stress analysis.

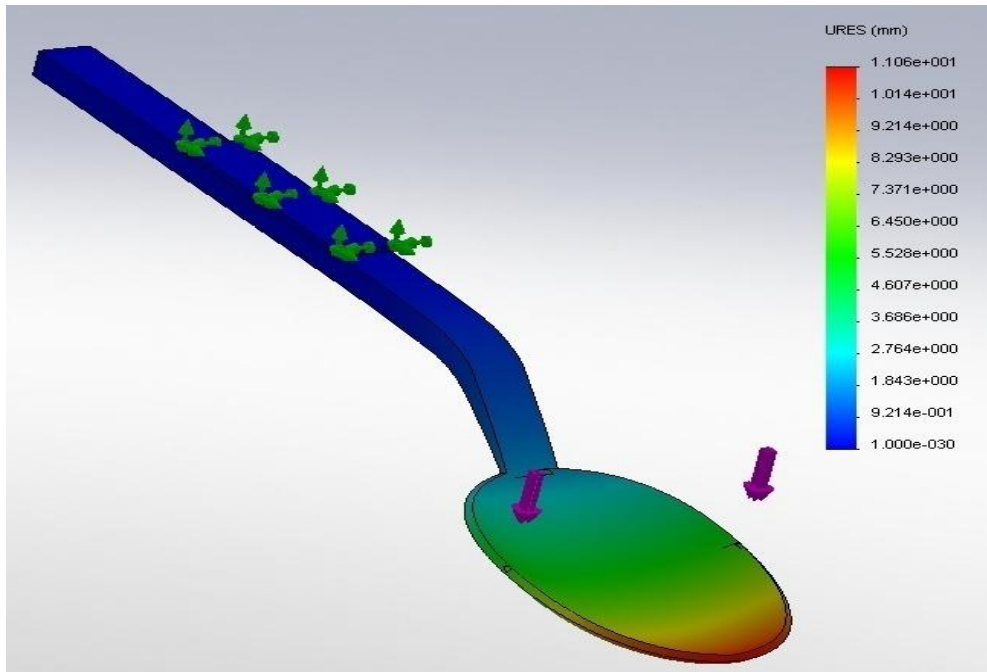


Figure 74. Eco-Products FEA spoon deflection results.

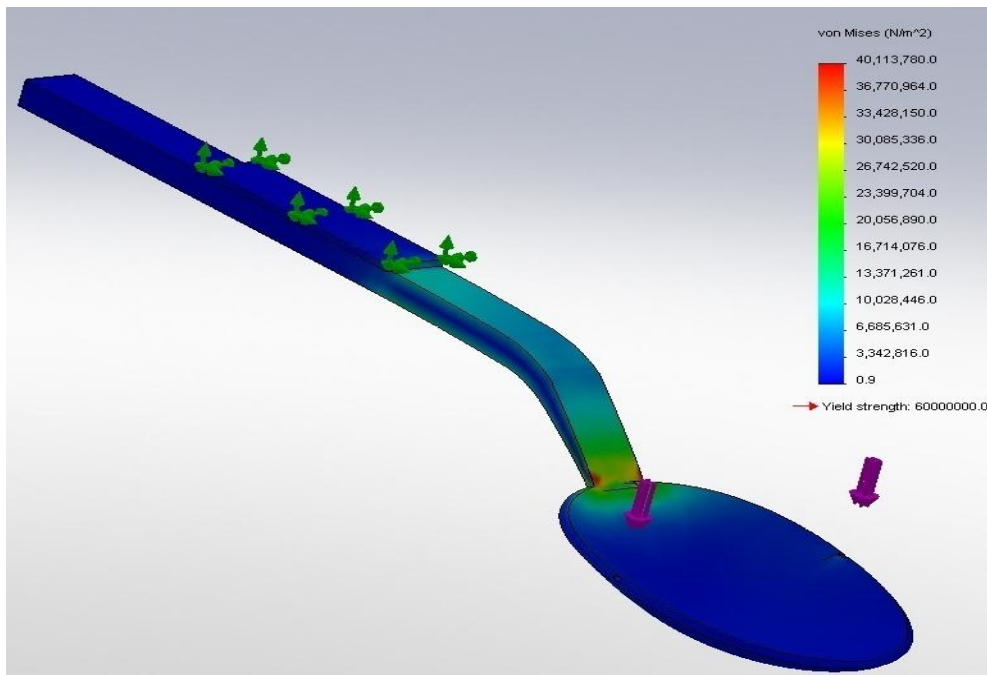


Figure 75. Eco-Products spoon stress analysis.

3.5 Creep Testing

Creep testing on both polystyrene and PLA were completed using ASTM Standard D2990-09 Standard Test Methods for Tensile, Compressive, and Flexural Creep and Creep-Rupture of Plastics. As Figures 76 and 77 indicate, polystyrene had a slightly larger amount of creep than the PLA resin. This can be attributed to the different mechanical properties associated with each material. In this case, the PLA had stronger properties than the polystyrene. Measurements were taken initially every few minutes, and then every few hours up to 1,000 hours.

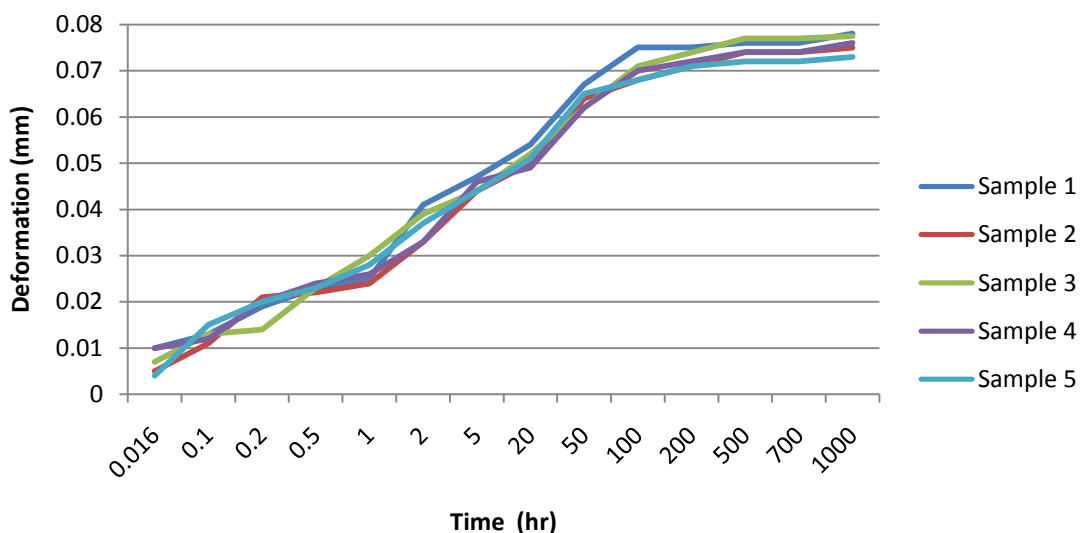


Figure 76. Polystyrene creep testing with 4.44 N load.

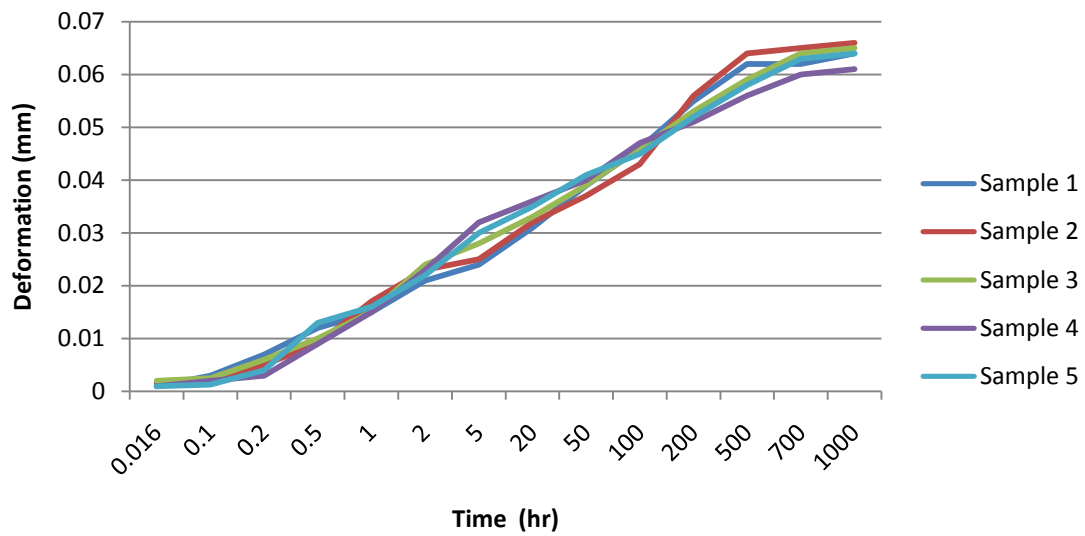


Figure 77. PLA creep testing with 4.44 N load.

In this case, the test shows that if the 4.44 N load is constantly applied to the utensil in the tensile direction, the PLA sample would lengthen at just under 0.07 mm, while the polystyrene sample would elongate at just under 0.08 mm. When searching for engineering materials, it is important that the creep rate remains low as this means the materials are not “growing” over time. It is seen that PLA and polystyrene samples have similar creep behavior.

CHAPTER 4. CONCLUSION

There is sufficient evidence at this time to indicate that biobased disposable plastic utensils performed differently than petrochemical plastic utensils. All of the biobased spoon utensils met CID specifications, while four out of six petrochemical spoons did not. All biobased and petrochemical forks met the CID specifications. Seven of the thirteen biobased knives met the CID specifications, while none of the petrochemical met the CID specifications.

After testing and statistical analysis, it appears that the biobased plastic (PLA) and petrochemical plastic polystyrene have similar mechanical properties, polypropylene, however, appears to be significantly different.

Statistical data indicate that with increases in biobased content and weight, the overall amount of deflection for forks, spoons, and knives decreases. One area that increases the weight of each utensil is the addition of support ribs in various locations on the utensil. However, as expected, the addition of support ribs results in less deflection under loading. Based on the utensils studied, biobased utensils manufacturers use more ribs in their designs compared to manufacturers of utensils molded from polypropylene or polystyrene. This may be the result of the designers' concern with preserved biobased PLA and their assurance of product acceptance by end users.

Finite Element Analysis results showed that the highest concentrations of stress occurred in the handle of the utensil for forks and knives, while spoons also had a high amount of stress where the handle joined the spoon bowl. Additionally, according to the models, there were low stress levels where the direct load was applied to the utensil. Much

of that can be attributed to the utensil overhanging from the vise and having no direct support features other than rib features already on the utensil.

Creep testing indicated that at room temperature and with a 4.4 N load applied to the utensil; the creep rate on the dogbone test sample was low. Another reason the creep rate stayed low on the utensil was because the load applied to the utensil was extremely low. If the load was increased on the utensil, the creep rate would have most likely increased as well.

4.1 Future Research

Future testing should include a study to determine the deflection of biobased utensils as a function of store time and conditions, as these materials are designed to degrade. It should also include testing more and equal amounts of biobased and conventional cutlery from companies that meet Type III length requirements in the Commercial Item Description. Several other tests should measure heat distortion, odor and taste testing, impact strength, and biodegradability and compostability. Further statistical work could be done to determine any correlations that exist between the thickness of the utensil, the relative amount of biobased content, and the amount of utensil deflection.

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Appendix A- Forks

Fk-a-5213-01	2.8	Fk-d-5213-01	1.9	Fk-g-5213-01	1.3	Fk-j-5213-01	4.5
Fk-a-5213-02	2.9	Fk-d-5213-02	2.1	Fk-g-5213-02	1.4	Fk-j-5213-02	3.8
Fk-a-5213-03	2.7	Fk-d-5213-03	2.2	Fk-g-5213-03	1.0	Fk-j-5213-03	3.8
Fk-a-5213-04	2.3	Fk-d-5213-04	2.2	Fk-g-5213-04	1.1	Fk-j-5213-04	3.8
Fk-a-5213-05	2.6	Fk-d-5213-05	1.6	Fk-g-5213-05	1.2	Fk-j-5213-05	4.3
Fk-a-5213-06	2.6	Fk-d-5213-06	2.2	Fk-g-5213-06	1.4	Fk-j-5213-06	3.6
Fk-a-5213-07	2.5	Fk-d-5213-07	1.7	Fk-g-5213-07	1.1	Fk-j-5213-07	3.9
Fk-a-5213-08	3.0	Fk-d-5213-08	2.3	Fk-g-5213-08	1.0	Fk-j-5213-08	3.7
Fk-a-5213-09	2.9	Fk-d-5213-09	1.9	Fk-g-5213-09	1.2	Fk-j-5213-09	3.2
Fk-a-5213-10	2.9	Fk-d-5213-10	2.4	Fk-g-5213-10	.41	Fk-j-5213-10	3.2
Fk-a-5213-11	3.2	Fk-d-5213-11	2.1	Fk-g-5213-11	1.2	Fk-j-5213-11	3.4
Fk-a-5213-12	2.7	Fk-d-5213-12	2.2	Fk-g-5213-12	.46	Fk-j-5213-12	3.6
Fk-a-5213-13	2.9	Fk-d-5213-13	1.8	Fk-g-5213-13	.87	Fk-j-5213-13	3.6
Fk-a-5213-14	2.7	Fk-d-5213-14	2.1	Fk-g-5213-14	.96	Fk-j-5213-14	3.8
Fk-a-5213-15	2.9	Fk-d-5213-15	1.8	Fk-g-5213-15	.86	Fk-j-5213-15	3.9
Fk-b-5213-01	2.5	Fk-e-5213-01	2.6	Fk-h-5213-01	2.5	Fk-k-5213-01	1.7
Fk-b-5213-02	2.6	Fk-e-5213-02	2.9	Fk-h-5213-02	2.6	Fk-k-5213-02	1.8
Fk-b-5213-03	2.5	Fk-e-5213-03	2.9	Fk-h-5213-03	2.4	Fk-k-5213-03	1.5
Fk-b-5213-04	2.8	Fk-e-5213-04	2.7	Fk-h-5213-04	2.6	Fk-k-5213-04	1.7
Fk-b-5213-05	2.3	Fk-e-5213-05	2.9	Fk-h-5213-05	2.2	Fk-k-5213-05	2.1
Fk-b-5213-06	2.8	Fk-e-5213-06	2.5	Fk-h-5213-06	2.3	Fk-k-5213-06	1.9
Fk-b-5213-07	2.7	Fk-e-5213-07	2.5	Fk-h-5213-07	2.4	Fk-k-5213-07	1.8
Fk-b-5213-08	2.9	Fk-e-5213-08	2.6	Fk-h-5213-08	2.4	Fk-k-5213-08	1.7
Fk-b-5213-09	3.3	Fk-e-5213-09	2.8	Fk-h-5213-09	2.0	Fk-k-5213-09	2.1
Fk-b-5213-10	3.2	Fk-e-5213-10	2.9	Fk-h-5213-10	2.0	Fk-k-5213-10	1.7
Fk-b-5213-11	2.9	Fk-e-5213-11	2.4	Fk-h-5213-11	1.8	Fk-k-5213-11	1.5
Fk-b-5213-12	3.4	Fk-e-5213-12	2.9	Fk-h-5213-12	1.9	Fk-k-5213-12	1.2
Fk-b-5213-13	3.0	Fk-e-5213-13	3.1	Fk-h-5213-13	2.6	Fk-k-5213-13	1.7
Fk-b-5213-14	3.3	Fk-e-5213-14	2.7	Fk-h-5213-14	2.1	Fk-k-5213-14	1.8
Fk-b-5213-15	2.4	Fk-e-5213-15	3.5	Fk-h-5213-15	2.8	Fk-k-5213-15	1.7
Fk-c-5213-01	1.7	Fk-f-5213-01	2.1	Fk-i-5213-01	2.0	Fk-l-5213-01	2.4
Fk-c-5213-02	1.3	Fk-f-5213-02	2.1	Fk-i-5213-02	2.3	Fk-l-5213-02	1.9
Fk-c-5213-03	1.5	Fk-f-5213-03	2.3	Fk-i-5213-03	2.9	Fk-l-5213-03	2.1
Fk-c-5213-04	1.5	Fk-f-5213-04	2.3	Fk-i-5213-04	3.5	Fk-l-5213-04	1.9
Fk-c-5213-05	1.6	Fk-f-5213-05	1.8	Fk-i-5213-05	2.5	Fk-l-5213-05	2.4
Fk-c-5213-06	1.4	Fk-f-5213-06	1.7	Fk-i-5213-06	3.1	Fk-l-5213-06	2.3
Fk-c-5213-07	1.5	Fk-f-5213-07	1.7	Fk-i-5213-07	2.2	Fk-l-5213-07	2.4
Fk-c-5213-08	1.3	Fk-f-5213-08	2.1	Fk-i-5213-08	2.1	Fk-l-5213-08	2.9
Fk-c-5213-09	1.5	Fk-f-5213-09	1.9	Fk-i-5213-09	3.1	Fk-l-5213-09	3.1
Fk-c-5213-10	1.9	Fk-f-5213-10	1.9	Fk-i-5213-10	2.6	Fk-l-5213-10	2.9
Fk-c-5213-11	2.0	Fk-f-5213-11	2.6	Fk-i-5213-11	2.5	Fk-l-5213-11	2.9
Fk-c-5213-12	1.7	Fk-f-5213-12	1.9	Fk-i-5213-12	2.4	Fk-l-5213-12	2.8
Fk-c-5213-13	1.7	Fk-f-5213-13	1.6	Fk-i-5213-13	2.6	Fk-l-5213-13	3.1
Fk-c-5213-14	2.1	Fk-f-5213-14	3.2	Fk-i-5213-14	2.7	Fk-l-5213-14	2.9
Fk-c-5213-15	1.9	Fk-f-5213-15	1.4	Fk-i-5213-15	2.7	Fk-l-5213-15	2.7

Appendix A- Forks Continued

Fk-m-5213-01	7.3	Fk-p-5213-01	7.7	Fk-s-5213-01	5.2
Fk-m-5213-02	7.9	Fk-p-5213-02	8.3	Fk-s-5213-02	4.3
Fk-m-5213-03	8.3	Fk-p-5213-03	6.9	Fk-s-5213-03	4.5
Fk-m-5213-04	6.9	Fk-p-5213-04	7.3	Fk-s-5213-04	5.2
Fk-m-5213-05	7.4	Fk-p-5213-05	7.5	Fk-s-5213-05	3.8
Fk-m-5213-06	7.1	Fk-p-5213-06	7.7	Fk-s-5213-06	4.8
Fk-m-5213-07	6.9	Fk-p-5213-07	7.3	Fk-s-5213-07	4.6
Fk-m-5213-08	7.3	Fk-p-5213-08	7.1	Fk-s-5213-08	4.3
Fk-m-5213-09	7.8	Fk-p-5213-09	8.1	Fk-s-5213-09	4.1
Fk-m-5213-10	8.2	Fk-p-5213-10	7.4	Fk-s-5213-10	4.5
Fk-m-5213-11	7.6	Fk-p-5213-11	7.7	Fk-s-5213-11	4.2
Fk-m-5213-12	8.1	Fk-p-5213-12	7.4	Fk-s-5213-12	3.9
Fk-m-5213-13	8.6	Fk-p-5213-13	7.1	Fk-s-5213-13	4.9
Fk-m-5213-14	7.9	Fk-p-5213-14	7.1	Fk-s-5213-14	5.2
Fk-m-5213-15	7.2	Fk-p-5213-15	7.9	Fk-s-5213-15	4.8
Fk-n-5213-01	3.2	Fk-q-5213-01	6.3		
Fk-n-5213-02	3.1	Fk-q-5213-02	6.6		
Fk-n-5213-03	3.1	Fk-q-5213-03	6.4		
Fk-n-5213-04	3.3	Fk-q-5213-04	6.5		
Fk-n-5213-05	3.3	Fk-q-5213-05	6.5		
Fk-n-5213-06	3.2	Fk-q-5213-06	6.7		
Fk-n-5213-07	3.1	Fk-q-5213-07	6.4		
Fk-n-5213-08	3.1	Fk-q-5213-08	6.3		
Fk-n-5213-09	2.9	Fk-q-5213-09	6.8		
Fk-n-5213-10	3.3	Fk-q-5213-10	6.7		
Fk-n-5213-11	3.2	Fk-q-5213-11	6.7		
Fk-n-5213-12	3.2	Fk-q-5213-12	6.8		
Fk-n-5213-13	3.0	Fk-q-5213-13	6.9		
Fk-n-5213-14	3.1	Fk-q-5213-14	6.8		
Fk-n-5213-15	3.1	Fk-q-5213-15	6.4		
Fk-o-5213-01	2.4	Fk-r-5213-01	2.9		
Fk-o-5213-02	2.5	Fk-r-5213-02	2.6		
Fk-o-5213-03	2.5	Fk-r-5213-03	2.6		
Fk-o-5213-04	2.7	Fk-r-5213-04	3.2		
Fk-o-5213-05	2.5	Fk-r-5213-05	2.3		
Fk-o-5213-06	2.5	Fk-r-5213-06	2.5		
Fk-o-5213-07	2.7	Fk-r-5213-07	3.5		
Fk-o-5213-08	2.8	Fk-r-5213-08	2.3		
Fk-o-5213-09	2.8	Fk-r-5213-09	3.5		
Fk-o-5213-10	2.8	Fk-r-5213-10	3.0		
Fk-o-5213-11	2.8	Fk-r-5213-11	3.1		
Fk-o-5213-12	2.7	Fk-r-5213-12	2.6		
Fk-o-5213-13	2.6	Fk-r-5213-13	2.7		
Fk-o-5213-14	2.8	Fk-r-5213-14	2.6		
Fk-o-5213-15	2.7	Fk-r-5213-15	2.6		

Appendix B- Knives

Kn-a-5214-01	56.2	Kn-d-5214-01	25.5	Kn-g-5214-01	9.09	Kn-j-5214-01	60.7
Kn-a-5214-02	55.9	Kn-d-5214-02	27.4	Kn-g-5214-02	12.8	Kn-j-5214-02	61.3
Kn-a-5214-03	56.1	Kn-d-5214-03	25.0	Kn-g-5214-03	12.7	Kn-j-5214-03	60.2
Kn-a-5214-04	55.8	Kn-d-5214-04	27.2	Kn-g-5214-04	13.8	Kn-j-5214-04	58.0
Kn-a-5214-05	53.5	Kn-d-5214-05	26.0	Kn-g-5214-05	13.2	Kn-j-5214-05	58.1
Kn-a-5214-06	52.7	Kn-d-5214-06	25.6	Kn-g-5214-06	13.5	Kn-j-5214-06	56.0
Kn-a-5214-07	54.8	Kn-d-5214-07	25.8	Kn-g-5214-07	13.2	Kn-j-5214-07	60.6
Kn-a-5214-08	54.1	Kn-d-5214-08	26.0	Kn-g-5214-08	13.4	Kn-j-5214-08	56.5
Kn-a-5214-09	52.7	Kn-d-5214-09	26.4	Kn-g-5214-09	13.4	Kn-j-5214-09	56.7
Kn-a-5214-10	54.7	Kn-d-5214-10	27.1	Kn-g-5214-10	13.4	Kn-j-5214-10	57.5
Kn-a-5214-11	55.3	Kn-d-5214-11	24.7	Kn-g-5214-11	13.2	Kn-j-5214-11	56.9
Kn-a-5214-12	54.7	Kn-d-5214-12	25.5	Kn-g-5214-12	12.8	Kn-j-5214-12	58.2
Kn-a-5214-13	54.4	Kn-d-5214-13	25.4	Kn-g-5214-13	12.2	Kn-j-5214-13	55.9
Kn-a-5214-14	54.2	Kn-d-5214-14	26.2	Kn-g-5214-14	13.6	Kn-j-5214-14	59.4
Kn-a-5214-15	52.5	Kn-d-5214-15	27.8	Kn-g-5214-15	12.9	Kn-j-5214-15	56.9
Kn-b-5214-01	53.7	Kn-e-5214-01	52.8	Kn-h-5214-01	36.3	Kn-k-5214-01	20.8
Kn-b-5214-02	52.3	Kn-e-5214-02	46.1	Kn-h-5214-02	39.5	Kn-k-5214-02	20.1
Kn-b-5214-03	58.3	Kn-e-5214-03	44.5	Kn-h-5214-03	35.8	Kn-k-5214-03	21.3
Kn-b-5214-04	56.2	Kn-e-5214-04	44.3	Kn-h-5214-04	37.9	Kn-k-5214-04	19.7
Kn-b-5214-05	57.1	Kn-e-5214-05	58.6	Kn-h-5214-05	39.3	Kn-k-5214-05	18.7
Kn-b-5214-06	55.0	Kn-e-5214-06	55.3	Kn-h-5214-06	38.2	Kn-k-5214-06	19.5
Kn-b-5214-07	55.8	Kn-e-5214-07	51.4	Kn-h-5214-07	35.4	Kn-k-5214-07	19.7
Kn-b-5214-08	53.7	Kn-e-5214-08	50.0	Kn-h-5214-08	37.7	Kn-k-5214-08	20.0
Kn-b-5214-09	54.2	Kn-e-5214-09	50.6	Kn-h-5214-09	37.8	Kn-k-5214-09	18.8
Kn-b-5214-10	57.7	Kn-e-5214-10	49.3	Kn-h-5214-10	37.5	Kn-k-5214-10	19.5
Kn-b-5214-11	56.5	Kn-e-5214-11	47.1	Kn-h-5214-11	38.0	Kn-k-5214-11	19.3
Kn-b-5214-12	55.0	Kn-e-5214-12	53.8	Kn-h-5214-12	38.9	Kn-k-5214-12	20.7
Kn-b-5214-13	57.3	Kn-e-5214-13	55.4	Kn-h-5214-13	35.0	Kn-k-5214-13	19.4
Kn-b-5214-14	52.8	Kn-e-5214-14	52.7	Kn-h-5214-14	37.5	Kn-k-5214-14	20.7
Kn-b-5214-15	52.2	Kn-e-5214-15	54.2	Kn-h-5214-15	40.0	Kn-k-5214-15	20.5
Kn-c-5214-01	14.5	Kn-f-5214-01	27.3	Kn-i-5214-01	38.2	Kn-l-5214-01	38.3
Kn-c-5214-02	12.7	Kn-f-5214-02	28.0	Kn-i-5214-02	39.8	Kn-l-5214-02	38.7
Kn-c-5214-03	15.1	Kn-f-5214-03	27.3	Kn-i-5214-03	38.8	Kn-l-5214-03	36.0
Kn-c-5214-04	17.0	Kn-f-5214-04	27.9	Kn-i-5214-04	36.5	Kn-l-5214-04	37.1
Kn-c-5214-05	16.9	Kn-f-5214-05	27.8	Kn-i-5214-05	37.7	Kn-l-5214-05	38.9
Kn-c-5214-06	19.7	Kn-f-5214-06	27.7	Kn-i-5214-06	40.2	Kn-l-5214-06	37.3
Kn-c-5214-07	17.3	Kn-f-5214-07	28.0	Kn-i-5214-07	40.0	Kn-l-5214-07	37.8
Kn-c-5214-08	17.7	Kn-f-5214-08	26.8	Kn-i-5214-08	38.2	Kn-l-5214-08	37.0
Kn-c-5214-09	18.6	Kn-f-5214-09	29.1	Kn-i-5214-09	37.0	Kn-l-5214-09	37.6
Kn-c-5214-10	17.8	Kn-f-5214-10	25.2	Kn-i-5214-10	36.9	Kn-l-5214-10	37.8
Kn-c-5214-11	17.9	Kn-f-5214-11	26.5	Kn-i-5214-11	36.4	Kn-l-5214-11	38.2
Kn-c-5214-12	17.9	Kn-f-5214-12	28.1	Kn-i-5214-12	39.8	Kn-l-5214-12	38.9
Kn-c-5214-13	17.0	Kn-f-5214-13	26.9	Kn-i-5214-13	36.5	Kn-l-5214-13	37.4
Kn-c-5214-14	16.8	Kn-f-5214-14	26.6	Kn-i-5214-14	36.1	Kn-l-5214-14	38.6
Kn-c-5214-15	17.3	Kn-f-5214-15	28.4	Kn-i-5214-15	40.0	Kn-l-5214-15	37.9

Appendix B-Knives Continued

Kn-m-5214-01	84.5	Kn-p-5214-01	72.7	Kn-s-5214-01	63.2
Kn-m-5214-02	87.9	Kn-p-5214-02	78.8	Kn-s-5214-02	51.1
Kn-m-5214-03	86.2	Kn-p-5214-03	76.9	Kn-s-5214-03	58.7
Kn-m-5214-04	85.1	Kn-p-5214-04	78.8	Kn-s-5214-04	64.8
Kn-m-5214-05	87.0	Kn-p-5214-05	76.9	Kn-s-5214-05	58.9
Kn-m-5214-06	86.8	Kn-p-5214-06	78.8	Kn-s-5214-06	62.4
Kn-m-5214-07	84.8	Kn-p-5214-07	77.8	Kn-s-5214-07	59.1
Kn-m-5214-08	88.8	Kn-p-5214-08	78.1	Kn-s-5214-08	60.4
Kn-m-5214-09	87.1	Kn-p-5214-09	77.3	Kn-s-5214-09	62.1
Kn-m-5214-10	85.2	Kn-p-5214-10	76.8	Kn-s-5214-10	61.1
Kn-m-5214-11	89.5	Kn-p-5214-11	78.1	Kn-s-5214-11	59.1
Kn-m-5214-12	89.7	Kn-p-5214-12	78.5	Kn-s-5214-12	56.9
Kn-m-5214-13	88.3	Kn-p-5214-13	76.2	Kn-s-5214-13	58.6
Kn-m-5214-14	87.9	Kn-p-5214-14	77.7	Kn-s-5214-14	58.6
Kn-m-5214-15	88.5	Kn-p-5214-15	78.7	Kn-s-5214-15	52.7
Kn-n-5214-01	59.4	Kn-q-5214-01	75.4		
Kn-n-5214-02	53.1	Kn-q-5214-02	68.8		
Kn-n-5214-03	53.9	Kn-q-5214-03	71.0		
Kn-n-5214-04	62.1	Kn-q-5214-04	72.3		
Kn-n-5214-05	51.9	Kn-q-5214-05	69.0		
Kn-n-5214-06	55.1	Kn-q-5214-06	72.8		
Kn-n-5214-07	53.7	Kn-q-5214-07	68.9		
Kn-n-5214-08	51.6	Kn-q-5214-08	71.6		
Kn-n-5214-09	55.0	Kn-q-5214-09	72.7		
Kn-n-5214-10	65.1	Kn-q-5214-10	75.2		
Kn-n-5214-11	53.4	Kn-q-5214-11	72.2		
Kn-n-5214-12	59.1	Kn-q-5214-12	72.8		
Kn-n-5214-13	54.7	Kn-q-5214-13	72.8		
Kn-n-5214-14	56.7	Kn-q-5214-14	72.6		
Kn-n-5214-15	62.3	Kn-q-5214-15	74.7		
Kn-o-5214-01	42.4	Kn-r-5214-01	51.6		
Kn-o-5214-02	43.0	Kn-r-5214-02	49.7		
Kn-o-5214-03	44.8	Kn-r-5214-03	50.9		
Kn-o-5214-04	40.7	Kn-r-5214-04	51.3		
Kn-o-5214-05	41.6	Kn-r-5214-05	50.7		
Kn-o-5214-06	44.2	Kn-r-5214-06	54.2		
Kn-o-5214-07	42.5	Kn-r-5214-07	51.5		
Kn-o-5214-08	44.4	Kn-r-5214-08	50.7		
Kn-o-5214-09	42.2	Kn-r-5214-09	54.2		
Kn-o-5214-10	43.4	Kn-r-5214-10	51.5		
Kn-o-5214-11	48.4	Kn-r-5214-11	45.1		
Kn-o-5214-12	46.2	Kn-r-5214-12	57.4		
Kn-o-5214-13	45.6	Kn-r-5214-13	55.0		
Kn-o-5214-14	46.6	Kn-r-5214-14	51.0		
Kn-o-5214-15	47.0	Kn-r-5214-15	50.6		

Appendix C-Spoons

Sp-a-5215-01	18.7	Sp-d-5215-01	9.5	Sp-g-5215-01	5.3	Sp-j-5215-01	20.0
Sp-a-5215-02	17.2	Sp-d-5215-02	9.4	Sp-g-5215-02	5.6	Sp-j-5215-02	20.8
Sp-a-5215-03	17.2	Sp-d-5215-03	9.7	Sp-g-5215-03	5.7	Sp-j-5215-03	21.2
Sp-a-5215-04	15.2	Sp-d-5215-04	10.4	Sp-g-5215-04	5.3	Sp-j-5215-04	20.1
Sp-a-5215-05	14.6	Sp-d-5215-05	10.3	Sp-g-5215-05	5.4	Sp-j-5215-05	21.7
Sp-a-5215-06	16.9	Sp-d-5215-06	10.7	Sp-g-5215-06	5.5	Sp-j-5215-06	20.9
Sp-a-5215-07	15.0	Sp-d-5215-07	9.7	Sp-g-5215-07	5.2	Sp-j-5215-07	20.8
Sp-a-5215-08	15.6	Sp-d-5215-08	9.3	Sp-g-5215-08	5.4	Sp-j-5215-08	21.5
Sp-a-5215-09	17.2	Sp-d-5215-09	9.9	Sp-g-5215-09	5.4	Sp-j-5215-09	21.9
Sp-a-5215-10	17.6	Sp-d-5215-10	10.6	Sp-g-5215-10	5.6	Sp-j-5215-10	21.0
Sp-a-5215-11	15.0	Sp-d-5215-11	10.2	Sp-g-5215-11	5.2	Sp-j-5215-11	22.2
Sp-a-5215-12	18.0	Sp-d-5215-12	10.8	Sp-g-5215-12	5.5	Sp-j-5215-12	19.7
Sp-a-5215-13	15.0	Sp-d-5215-13	10.3	Sp-g-5215-13	5.5	Sp-j-5215-13	21.8
Sp-a-5215-14	18.3	Sp-d-5215-14	9.9	Sp-g-5215-14	5.5	Sp-j-5215-14	20.5
Sp-a-5215-15	15.8	Sp-d-5215-15	11.0	Sp-g-5215-15	5.4	Sp-j-5215-15	21.2
Sp-b-5215-01	18.5	Sp-e-5215-01	14.6	Sp-h-5215-01	11.2	Sp-k-5215-01	9.5
Sp-b-5215-02	18.1	Sp-e-5215-02	15.1	Sp-h-5215-02	11.6	Sp-k-5215-02	8.9
Sp-b-5215-03	18.3	Sp-e-5215-03	14.6	Sp-h-5215-03	11.8	Sp-k-5215-03	10.5
Sp-b-5215-04	18.5	Sp-e-5215-04	16.1	Sp-h-5215-04	11.4	Sp-k-5215-04	10.3
Sp-b-5215-05	17.5	Sp-e-5215-05	16.9	Sp-h-5215-05	11.5	Sp-k-5215-05	9.4
Sp-b-5215-06	17.2	Sp-e-5215-06	15.3	Sp-h-5215-06	11.7	Sp-k-5215-06	8.2
Sp-b-5215-07	18.2	Sp-e-5215-07	16.1	Sp-h-5215-07	11.2	Sp-k-5215-07	9.3
Sp-b-5215-08	15.9	Sp-e-5215-08	14.9	Sp-h-5215-08	11.0	Sp-k-5215-08	9.6
Sp-b-5215-09	17.6	Sp-e-5215-09	16.4	Sp-h-5215-09	11.7	Sp-k-5215-09	10.2
Sp-b-5215-10	15.7	Sp-e-5215-10	15.6	Sp-h-5215-10	11.2	Sp-k-5215-10	10.3
Sp-b-5215-11	17.6	Sp-e-5215-11	14.8	Sp-h-5215-11	11.9	Sp-k-5215-11	9.6
Sp-b-5215-12	18.4	Sp-e-5215-12	16.8	Sp-h-5215-12	11.3	Sp-k-5215-12	10.2
Sp-b-5215-13	18.1	Sp-e-5215-13	15.5	Sp-h-5215-13	11.7	Sp-k-5215-13	8.3
Sp-b-5215-14	16.7	Sp-e-5215-14	15.2	Sp-h-5215-14	11.3	Sp-k-5215-14	9.7
Sp-b-5215-15	17.3	Sp-e-5215-15	16.7	Sp-h-5215-15	11.8	Sp-k-5215-15	10.6
Sp-c-5215-01	8.6	Sp-f-5215-01	10.1	Sp-i-5215-01	13.1	Sp-l-5215-01	15.2
Sp-c-5215-02	7.9	Sp-f-5215-02	10.8	Sp-i-5215-02	15.1	Sp-l-5215-02	14.4
Sp-c-5215-03	9.3	Sp-f-5215-03	11.2	Sp-i-5215-03	14.7	Sp-l-5215-03	13.6
Sp-c-5215-04	7.2	Sp-f-5215-04	11.5	Sp-i-5215-04	14.1	Sp-l-5215-04	14.0
Sp-c-5215-05	7.6	Sp-f-5215-05	10.9	Sp-i-5215-05	13.8	Sp-l-5215-05	13.1
Sp-c-5215-06	7.2	Sp-f-5215-06	10.5	Sp-i-5215-06	14.4	Sp-l-5215-06	14.2
Sp-c-5215-07	8.0	Sp-f-5215-07	10.6	Sp-i-5215-07	14.9	Sp-l-5215-07	13.3
Sp-c-5215-08	7.4	Sp-f-5215-08	11.9	Sp-i-5215-08	13.9	Sp-l-5215-08	13.8
Sp-c-5215-09	8.2	Sp-f-5215-09	10.4	Sp-i-5215-09	15.1	Sp-l-5215-09	13.5
Sp-c-5215-10	6.8	Sp-f-5215-10	12.1	Sp-i-5215-10	12.8	Sp-l-5215-10	13.7
Sp-c-5215-11	7.0	Sp-f-5215-11	10.8	Sp-i-5215-11	14.1	Sp-l-5215-11	13.3
Sp-c-5215-12	7.8	Sp-f-5215-12	11.0	Sp-i-5215-12	13.6	Sp-l-5215-12	13.0
Sp-c-5215-13	7.1	Sp-f-5215-13	10.5	Sp-i-5215-13	14.7	Sp-l-5215-13	14.5
Sp-c-5215-14	8.3	Sp-f-5215-14	10.7	Sp-i-5215-14	14.4	Sp-l-5215-14	14.1
Sp-c-5215-15	7.5	Sp-f-5215-15	11.1	Sp-i-5215-15	13.2	Sp-l-5215-15	13.6

Appendix C-Spoons Continued

Sp-m-5215-01	64.4	Sp-p-5215-01	33.7	Sp-s-5215-01	29.0
Sp-m-5215-02	63.4	Sp-p-5215-02	32.1	Sp-s-5215-02	31.2
Sp-m-5215-03	64.9	Sp-p-5215-03	35.4	Sp-s-5215-03	30.2
Sp-m-5215-04	65.2	Sp-p-5215-04	34.5	Sp-s-5215-04	30.5
Sp-m-5215-05	63.0	Sp-p-5215-05	31.9	Sp-s-5215-05	32.8
Sp-m-5215-06	64.2	Sp-p-5215-06	33.6	Sp-s-5215-06	29.7
Sp-m-5215-07	65.6	Sp-p-5215-07	35.3	Sp-s-5215-07	30.7
Sp-m-5215-08	66.0	Sp-p-5215-08	31.9	Sp-s-5215-08	29.5
Sp-m-5215-09	65.1	Sp-p-5215-09	34.7	Sp-s-5215-09	30.3
Sp-m-5215-10	64.2	Sp-p-5215-10	33.0	Sp-s-5215-10	27.9
Sp-m-5215-11	63.7	Sp-p-5215-11	31.2	Sp-s-5215-11	27.5
Sp-m-5215-12	64.3	Sp-p-5215-12	33.5	Sp-s-5215-12	32.7
Sp-m-5215-13	65.4	Sp-p-5215-13	31.1	Sp-s-5215-13	27.4
Sp-m-5215-14	64.6	Sp-p-5215-14	31.7	Sp-s-5215-14	27.8
Sp-m-5215-15	65.4	Sp-p-5215-15	32.1	Sp-s-5215-15	30.9
Sp-n-5215-01	20.0	Sp-q-5215-01	32.0		
Sp-n-5215-02	19.4	Sp-q-5215-02	33.1		
Sp-n-5215-03	17.9	Sp-q-5215-03	32.8		
Sp-n-5215-04	17.3	Sp-q-5215-04	31.8		
Sp-n-5215-05	15.4	Sp-q-5215-05	31.8		
Sp-n-5215-06	18.6	Sp-q-5215-06	31.9		
Sp-n-5215-07	17.2	Sp-q-5215-07	33.3		
Sp-n-5215-08	18.8	Sp-q-5215-08	34.3		
Sp-n-5215-09	19.7	Sp-q-5215-09	30.0		
Sp-n-5215-10	18.9	Sp-q-5215-10	32.8		
Sp-n-5215-11	17.2	Sp-q-5215-11	30.5		
Sp-n-5215-12	17.8	Sp-q-5215-12	31.2		
Sp-n-5215-13	16.3	Sp-q-5215-13	31.7		
Sp-n-5215-14	17.2	Sp-q-5215-14	30.7		
Sp-n-5215-15	18.0	Sp-q-5215-15	30.6		
Sp-o-5215-01	13.9	Sp-r-5215-01	16.1		
Sp-o-5215-02	12.9	Sp-r-5215-02	15.5		
Sp-o-5215-03	13.8	Sp-r-5215-03	16.6		
Sp-o-5215-04	13.0	Sp-r-5215-04	15.2		
Sp-o-5215-05	14.4	Sp-r-5215-05	15.4		
Sp-o-5215-06	14.6	Sp-r-5215-06	15.7		
Sp-o-5215-07	13.7	Sp-r-5215-07	16.8		
Sp-o-5215-08	15.3	Sp-r-5215-08	15.0		
Sp-o-5215-09	14.1	Sp-r-5215-09	16.6		
Sp-o-5215-10	13.7	Sp-r-5215-10	16.3		
Sp-o-5215-11	14.9	Sp-r-5215-11	15.7		
Sp-o-5215-12	14.7	Sp-r-5215-12	16.5		
Sp-o-5215-13	14.3	Sp-r-5215-13	15.8		
Sp-o-5215-14	15.0	Sp-r-5215-14	15.0		
Sp-o-5215-15	15.2	Sp-r-5215-15	15.5		

Appendix D-Companies

Company	Brand	Resin Type
A	All Things Renewable Eco-Brand	Biobased
B	BioSmart 200F Heat Tolerance	Biobased
C	Branch 200F Heat Tolerance	Biobased
D	GREENCulture Nat-Ur Eco Cutlery	Biobased
E	Eco-Products 220F Heat Tolerance	Biobased
F	Greenwave	Biobased
G	Nature Friendly	Biobased
H	Jaya	Biobased
I	Spudware	Biobased
J	Dixie	Conventional
K	World Centric 200F Heat Tolerance	Biobased
L	Branch	Biobased
M	Kitchen Cutlery	Conventional
N	Genuine Joe	Conventional
O	Biomass-75	Biobased
P	Dart	Conventional
Q	Penley	Conventional
R	Conserve	Biobased
S	Premierware	Conventional