ECOLOGICAL PLASTIC MATERIALS AND THEIR SUITABILITY FOR HOUSEWARE APPLICATIONS

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Ecological plastic materials and their suitability for houseware applications

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ABSTRACT

The purpose of this study was to investigate ecological plastic materials. The aim was to identify what kind of bio-based plastics and natural fiber composites are available, and to narrow down the potential ones for further analysis. In this thesis material suitability was evaluated according agreed requirements, and the ecology of the materials was compared to plastics that are commonly used in houseware applications.

The theoretical part of the thesis consists of two larger sub-sections, ecological plastic materials and presentation and evaluation of ways to evaluate sustainability. In the first sub-section, concepts of bioplastics and natural fiber composites are clarified and their opportunities and constraints are described. In the second sub-section, two different ways to evaluate sustainability are presented: renewable/bio-based content of the materials measured in percentages, and life cycle assessment.

The practical part starts with comparison of the life cycle assessments of different materials. The aim was to investigate if there really are ecological benefits achievable when replacing the old material with a new one. The practical part also included testing the new materials on an actual product. Due to the confidential reasons, test results couldn't be published.

Key words: bioplastic, natural fiber composite, life cycle assessment, USDA label, ecological, sustainable

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Muovitekniikan koulutusohjelma

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TIIVISTELMÄ

Tämän opinnäytetyön tarkoituksena on tutkia ekologisia. Tavoitteena on kartoittaa, millaisia biopohjaisia muoveja ja luonnonkuitukomposiitteja on tarjolla sekä rajata niistä potentiaalisimmat tarkempaa tutkimusta varten. Työssä arvioidaan materiaalien soveltuvuutta sovittujen vaatimusten mukaisesti sekä vertaillaan materiaalien ekologisuutta nykyisin kotitaloustarvikkeissa käytettäviin muovilaatuihin.

Opinnäytetyön teoriaosa koostuu kahdesta suuremmasta osa-alueesta: ekologisten muovimateriaalien esittelystä ja ekologisuuden arvioimisen keinoista. Ensimmäisessä selvennetään biomuovin ja luonnonkuitukomposiittien käsitteitä sekä kerrotaan niiden mahdollisuuksista ja rajoitteista. Keinoja ekologisuuden arvioimiseen esitellään kaksi: materiaalin prosentuaalinen biopohjaisuus ja elämänkaarianalyysi.

Käytännön osuus alkaa elämänkaarianalyysien vertailusta, jonka tarkoituksena on selvittää materiaalin vaihtamisesta syntyvät ekologiset hyödyt. Käytännön osuuteen kuuluu myös materiaalin testaaminen tuotteessa. Luottamuksellisista syistä testituloksia ei ole lupaa julkaista.

Avainsanat: Bioplastic, natural fiber composite, life cycle assessment, USDA label, ecological, sustainable

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TERMINOLOGY

Bioplastic: Plastics that are made partly or entirely from ingredients derived from living, renewable sources.

Biodegradable plastic: Biodegradable plastics are caused to degrade because of the action of micro-organisms and enzymes. In order for these materials to degrade effectively, high enough temperature and right conditions are required. These materials start to biodegrade in household composts but this is no recommended since the process is slow.

Compostable plastic: Plastics that degrade easily by the cause of biological process that happens during composting.

Natural fiber composite: Combination material where plastic and fibers from different renewable sources are mixed together. These materials can be processed like conventional plastics.

LCA: Life cycle assessment is a research method which can be used to measure environmental impacts of products or services.

Ecological: Product or service has smaller negative impact on nature than a conventional equivalent.

Sustainable: Product or service is carried out with minimal effect on environment without its volume or quality being reduced.

PP: Polypropylene. A cheap mass plastic which is used in various applications such as handles of kitchen utensils.

PBT: Polybuthylene terephtelate. More technical and expensive plastic than PP. PBT has better mechanical, thermal and chemical properties. It is commonly used in demanding mechanical applications

1 INTRODUCTION

Since the petroleum resources are decreasing, ecological awareness is growing and new environmental regulations are made, interest towards new green materials is at its peak. The Waste disposal problem and regulations for cleaner and safer environment have increased the research of bio based or otherwise more sustainable materials. Many companies today have taken sustainability and green values as part of their operating standards.

1.1 Objectives

There were three key drivers of the project: providing more environmentally friendly material options for consumers, understanding of the current availability of eco materials and their suitability for houseware products, and environmental responsibility in general.

1.2 Scope

The target of the project was to search for ecological/sustainable plastic materials for kitchen ware applications and to determine their suitability for houseware products. Such a material should have a smaller carbon footprint or similar environmental indicator and equal or improved mechanical properties than the material being applied at the moment.

There were four materials evaluated in this project, three bio-based plastics and one natural fiber composite. Materials were chosen on the basis of their mechanical properties and appearance. Mechanical properties were evaluated by testing them according to agreed requirements using typical materials as reference. In addition, sustainability of the new materials was compared to the originals. It was clear from the beginning that all the materials to be tested are usually more expensive than materials currently applied, but materials are expected to become more affordable in the future. Part of the project was also to compare the current prices of the tested materials to the prices of currently used materials.

2 ECOLOGICAL PLASTIC MATERIALS

There are three subsets of plastic materials that are considered more ecological than traditional plastics: bioplastics, natural fiber composites and recycled plastics. This project concentrates on bioplastics and natural fiber composites and therefore recycled plastics are not discussed.

2.1 Biopolymers and bioplastics

The thing that differ biopolymers from petro-polymers is that monomers of a biopolymer are derived from a living source rather than from oil. Bioplastics are made from biopolymers by mixing them with plasticizers and other additives. Some bioplastics are identical to petro-plastics. For example, bio-polyethylene (bio-PE) has the same chemical structure as its equivalent in petro-plastics. There are also bioplastics that are unique and have no equivalent in petro-plastics. (Momani 2009, 16, Stevens 2002, 104.)

The term bioplastics can mean two things: compostable plastics that are made from renewable or nonrenewable resources and bio-based plastics produced from renewable resources. The focus of the first group is on their compostability and the focus of the second croup is on their raw material basis. Compostable plastics are certified according to EN13432, the legally binding standard for the compostability of plastics in all EU member states. (European bioplastics 2008, 3.)

It is important to understand the difference between biodegradable plastics and compostable plastics. Biodegradable plastics are caused to degrade because of the action of micro-organisms and enzymes. In order for these materials to degrade, a high enough temperature and right conditions are required. In compostable plastics, degrading is caused by a biological process that occurs during composting. It should also be noted that not all bio-based plastics are biodegradable and traditional petroplastics can also be biodegradable. (Pro Europe 2009.)

There are many biological resources that can function as feedstock for bioplastics. Corn, potatoes, rice, barley, sorghum and wheat are typical feedstock for starch based bioplastics. Starch-based bioplastics can be subdivided to two groups.The difference between these two groups is that on is made from starch itself and the other is formed from starch-sugar fermentation products. Starch-based bioplastics are used for manufacturing the same kind of applications as are made from polyethylene and polystyrene. Typical products are disposable cutlery, plastic bags and food packaging. The most common way to produce starch-based plastics is heating starch with a plasticizer, such as glycerol, under shear force. Starch-sugar-based plastics are manufactured by using sugar from starch as a nutrient in bacterial fermentation processes. Most commonly known starch-sugar based bioplastics are polylactic acid (PLA) and polyhydroxyalkanotes (PHA). (Barker & Stafford 2009, 62-, 63; Momani 2009, 16.)

Besides starch, bioplastics can also be made from other renewable feedstock. Cellulose, commonly sourced from wood pulp, hemp and cotton, can be used for making bioplastics after chemical modification. A typical cellulose-based bioplastic is cellulose acetate (CA). Lignin-based bioplastics are made from lignocellulosic plant material that is formed as a byproduct of the paper industry. Also plant proteins like maize can be used to manufacture bioplastics. Plastics using starch, cellulose, lignin or plant proteins as their feedstock are typically biodegradable and can be broken down in the environment by micro-organisms.
(Barker, Stafford, Burgner & Edwards 2009, 2.)

Non-biodegradable bioplastics are manufactured using bio-oils like castor, soya been, or oilseed rape oil. Similar resins to petro-based plastics can be made from compounds extracted from these plant oils. Typical bio-oil-based plastics include polyamides (PA) and polyurethanes (PU). Even though partly bio-based polytrimethylene terephtelate (PTT) uses corn starch as its feedstock it is not biodegradable. Another exception is bio-polyethylene, which is also non-biodegradable, and it is made from bio-ethanol. (Barker, Stafford, Burgner & Edwards 2009, 2.)

2.1.1 Disposal options for bioplastics

In order to achieve maximum environmental benefit from bioplastics, it is important to dispose them in a correct way. Disposal options are the same for bioplastics and petro-plastics except that some bioplastics can be composted. Different options for bio and petroplastics disposal are presented in Figure 1. (Barker, Stafford, Burgner & Edwards 2009, 3.)

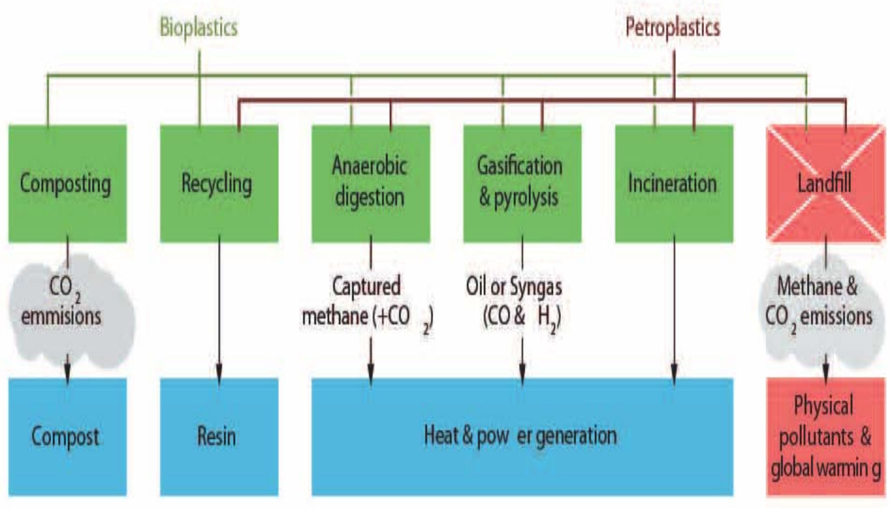


FIGURE 1. Different options for disposal of bio-, and petro-plastics. (Barker, Stafford, Burgner & Edwards 2009, 4.)

With the help of labeling system, identifying bioplastics has been made easier for consumers. Labels also indicate how these materials should be disposed. Some bioplastics are labeled with number seven surrounded by a triangle and a text “other” below it. This logo is the first one on the left in Figure 2. This sign is also used for other materials that are not bio-based and it does not give any information on how the material should be disposed. There are options for labeling that give more information. “Seedling logo” in the middle of Figure 2 indicates that the material disintegrates and biodegrades in industrial conditions. The other two labels in the picture show that the labeled product is home compostable and biodegradable. (Barker, Stafford, Burgner & Edwards 2009, 3.)

FIGURE 2. Options for labeling bioplastics. (Barker, Stafford, Burgner & Ed wards 2009, 3.)

At the moment, the ideal way to dispose bioplastics is through industrial composting, landfill being the least recommended way. Composting in home is challenging because high enough temperatures might not be reached to make the material biodegrade. Anaerobic digestion provides an alternative for composting. In this method, organic materials can be biodegraded in the absence of air. Methane formed during the process is captured and burned to generate energy. (Barker, Stafford, Burgner & Edwards 2009, 3.)

Recycling is a good option for disposal for some bioplastics such as bio-based polyamide (PA) and polylactic acid (PLA). The problem with PLA's recycling is that if PLA gets mixed in the polyethylene terephtalate's (PET) recycling stream it contaminates PET and makes it unusable. (Barker, Stafford, Burgner & Edwards 2009, 3.)

Bioplastics can be used to generate heat and power with methods such as incineration, pyrolysis and gasification. To minimize environmental impact in incineration, materials to be burned have to be chosen carefully and you have to make sure that furnace conditions are suitable. In pyrolysis, organic materials are decomposed by heating them in the absence of air and in gasification there is controlled air content. Both produce carbon monoxide and hydrogen but the difference is that in pyrolysis these substances are turned into burnable oil and in gasification carbon monoxide and hydrogen are burned directly. (Barker, Stafford, Burgner & Edwards 2009, 3.)

Depending on the grade, bioplastics have many environmental and functional benefits over petro-plastics, but some aspects are still problematic. Probably the biggest problem is that bioplastics are still a lot more expensive than conventional plastics. The Scale of produced bioplastics is increasing and if their popularity continues to crow, prices are expected to get lower. Another problem is that biop-lastics are relatively new industry and therefore bioplastics end of use disposal methods are not familiar to consumers and industries. This leads to a situation where bioplastics end up in landfills. (Barker, Stafford, Burgner & Edwards 2009, 5.)

2.2 Potential bioplastics to be used in houseware applications

Materials that are viewed in this chapter were considered to have most potential to be used for houseware applications. The chapter covers three materials in more detail: polylactic acid (PLA), bio-based polyamides (bio-PA), and bio-based poly trimethylene terephtelate (PTT). In addition, other bioplastics that were not consi-dered to be suitable are presented shortly at the end of this chapter.

2.2.1 Polylactic acid or PLA

Polylactic acid is most commonly made from corn starch. It is a biodegradable, naturally transparent plastic that can be colored. It resembles conventional petro-chemical mass plastics (like PE or PP) and it can also be converted easily on stan-dard equipment like injection molding, blow molding and deep-drawing machines that are commonly used for production of petro-plastics. PLA’s properties can be changed with additives, which expands the variety of products it can be used in. PLA plastics are most commonly used for short lived packaging like yoghurt cups. It also has potential uses in medical and textile industries. (Platt 2006, 21; bioplastics.org 2011.)

PLA is one of the most versatile bioplastics and it has a wide range of properties. Its biodegradability can be changed so that some grades biodegrade quickly and some take years to degrade. The main disadvantage of PLA is that it softens at the temperature of 60 degrees Celsius. However, higher softening temperatures can be achieved by copolymerization with a more heat resistant polymer or by adding fillers. The most common way to reinforce PLA is with glass fiber which provides great improvements in mechanical and thermal properties. Effects of glass fiber as reinforcement can be viewed form Table 1. (Bioplastics.org 2011.)

TABLE 1. Glass fiber reinforced PLA compared to some other glass fiber reinforced plastics and unreinforced PLA. (RTP 2011, 3.)

Comparison of 30% Glass Fiber Reinforced Compounds

	Unmodified PLA	30% GF PP	30% GF PLA *	30% GF PBT
Tensile Strength	9,000 psi 62 MPa	11,000 psi 76 MPa	16,500 psi 114 MPa	18,000 psi 124 MPa
Flexural Strength	15,700 psi 108 MPa	16,200 psi 112 MPa	21,000 psi 145 MPa	27,500 psi 190 MPa
Flexural Modulus	555,000 psi 3,828 MPa	700,000 psi 4,826 MPa	1,630,000 psi 11,239 MPa	1,200,000 psi 8,274 MPa
Impact Resistance, Izod Notched 1/8 in (3.2 mm)	0.3 ft-lbs/in 16 J/m	2.0 ft-lbs/in 107 J/m	1.0 ft-lbs/in 53 J/m	1.8 ft-lbs/in 96 J/m
Heat Deflection Temperature @ 66 psi (455 kPa)	124°F 51°C	315°F 157°C	320°F 160°C	415°F 213°C

There are three main ways to produce PLA: condensation, azeotropic condensation, and ring opening polymerization. The outcome in all the alternative production methods is the same high molecular weight PLA, the chemical structureof which is presented in Figure 3.

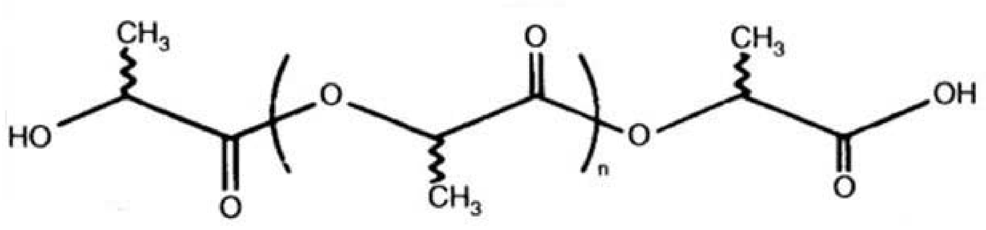


FIGURE 3. High molecular weight PLA (Mittal 2010, 256.)

2.2.2 Bio-based polyamides or nylons

Nylon is a common name for all long-chain polyamide engineering thermoplastics which have amide groups [-CO-NH-] in their polymer chain. Bio-based and petroleum-based polyamides have similar properties and are used in same kind of applications. Neither one is biodegradable but they are recyclable. Fibers, automotive parts, kitchen utensils, electronic uses and packaging are typical applications for nylon. Currently bio-PAs can't be applied to some kitchen utensils because there are no food contact safe grades available. Typically handle parts of houseware products are not required to be made from food contact safe materials. In such products food contact safety applies only to blade parts. Target applications for some bio-based PA grades can be viewed from Figure 5. (Wolf 2005, 105.)

There are many grades of bio-based polyamides currently available that use castor oil as their feedstock. Castor oil is derived from the castor plant, which is not a food crop and it is not competing with food crops for land. Polyamides made from castor oil have high bio content varying from 48 % to 99 % on from the grade and fillers. Properties are similar to traditional polyamides and can be modified whit additives and fibers such as glass fibers. The chemical structure of bio-based PA 1010 from castor oil is presented in Figure 4. (Sturzel 2011, 2-4.)

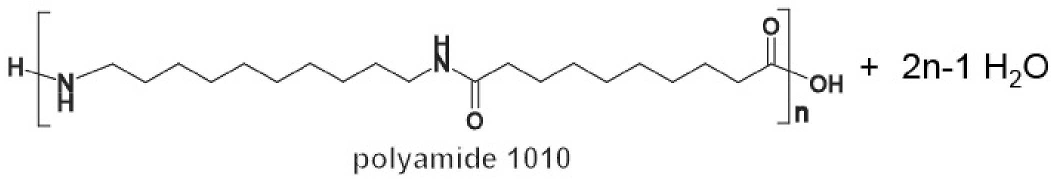


FIGURE 4. Bio-based polyamide 1010 from castor oil derivative decane diamine and sebacic acid. (Sturzel 2011, 22.)

FIGURE 5. Some target applications for bio-based polyamide. (Sturzel 2011, 16.)

2.2.3 Polytrimethylene terephtelate or PTT from bio-based PDO

Polytrimethylene terephtelate, or PTT, is an aromatic polyester, which is produced by polycondensation of 1,3-propanediol (trimethylene glycol or PDO) with purified terephtalic acid (PTA) or dimethyl terephtelate (DMT). PTA and DMT are always derived from petrochemical feedstock but PDO is can be derived from renewable resources. Bio-based PDO is made with an aerobic bioprocess with glucose from corn starch as feedstock. The chemical structure of PTT is presented in Figure 6. (Wolf 2005, 67.)

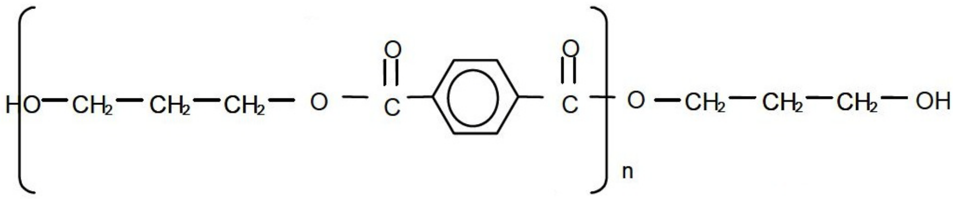


FIGURE 6. Chemical structure of PTT. (Wolf 2005, 69.)

PTT has a good combination of properties, which makes it a very worthwhile alternative to be used in technical applications. Its rigidity, heat resistance and strength can be compared to PET’s properties and it is as easy to process as PBT.

Fibers made from PTT are used to make carpets and industrial textiles which have to have good resiliency, wearability, static and chemical resistance and dyeability. PTT's properties can be altered by mixing it with other resins to make it more suitable for injection molding and extrusion applications. (Wolf 2005, 67.)

2.2.4 Other bioplastics

There are several other grades of bio-based plastics that are only presented here shortly because they lack the mechanical or chemical properties required for houseware applications or they are still too expensive to produce. In order to get a full picture of the bioplastic market today, these materials were still chosen to be included in this project. These materials might also be potential candidates for other products or packaging. Such materials are: polyhydroxyalkonoates (PHAs), bio-based polyurethane (PUR), bio-based polybutylene succianate (PBS), bio-based PBT, cellulose acetate (CA) and bio-based polyethylene (PE).

PHA is a bio-based biodegradable plastic that is made from renewable resources and it's usually manufactured by bacterial fermentation of biomass. PHA copolymers have good processability and can be converted to various products such as films, fibers, molded articles and coating materials. PHA copolymers are a promising alternative in applications where non-toxicity and biodegradability are key factors. The most commonly known products made from PHA are garbage bags, packaging and single-use food containers. (Cheng 2010, 251, 253.)

Conventional polyurethanes are made from two components, polyol and isosyanate which are both derived from petrochemical feedstock. There are a lot of different grades of PURs and for some applications the polyol component can be derived from vegetable-oils. These oils can be manufactured from such plants as castor plant, soy bean, sunflower and linseed. At the moment, castor oil is the most widely used feedstock for bio-based PUR. However, the PURs made in such a way have limited usability because the resins have limited hardness and other mechanical properties. The market share of bio-based PURs is expected to increase as new feedstock possibilities and applications are found. (Wolf 2005, 95-96.)

PBS is traditionally synthesized by polycondensation between succinic acid butanediol. These monomers are also possible to obtain from renewable resources trough fermentation. PBS is biodegradable and bio-compostable and in the near future bio-based commercial grades might be available. PBS has many similar properties to LD-PE, HD-PE and PP and it can be processed with conventional equipment such as injection- and blow molding machines. Therefore it is considered to be a potential alternative to some petro plastics. (Kutz 2011, 153; Ma 2011, 8.)

Polybutelyne terephtelate (PBT) can be produced from bio-based 1,4-butanediol (BDO), but the process is still too expensive compared to the conventional way of producing PBT from dimethyl terephtelate and BDO. In the future, if the process can be made more economically viable and bio-based PBT has the same set of properties as petro-based PBT, bio-based PBT can replace conventional PBT altogether. (Wolf 2005, 75-76.)

Cellulose acetate is a modified polysaccharide which is formed when acetic anhydride reacts with wood pulp or cotton linters. The tensile strength of cellulose acetate is close to polystyrene. With the help of plasticizers, it can be processed with typical equipment of the plastic industry. It can be used in coatings, adhesive tapes, tool handles and spectacle frames. (Moore, Saunders 1997, 25.)

Bio-based PE is made from ethanol that is obtained from the fermentation process of corn or sugar cane. Bio-PE is chemically and physically identical to conventionally produced PE so it is not biodegradable but it can be recycled. It is claimed that bio-based PE is environmentally superior to petro-based PE. (Wikipedia 2011.)

2.3 Natural fiber composites

In this context, natural fiber composites mean combinations of natural fibers and plastic materials rather than fiber mats laminated together. In these materials, plastic is used as a matrix material in which fibers are mixed. A wide range of natural fibers are available from plant and animal resources. When used in plastic composites, these fibers provide a great reinforcement to the new material. Natural fibers have been used to reinforce plastics for many years but are still less popular than synthetic fibers such as glass and carbon fibers. The main reason for this is that natural fibers do not have as good mechanical properties as man-made fibers so they are needed more to achieve the same strength in composite material. Interest in natural fibers has increased lately because of environmental reasons. Natural fiber composites can be processed with the same equipment as conventional plastics. In Figure 7, there are some injection molded cutlery and tableware products made from polypropylene reinforced with 50 percent pine fiber. (Pothan 2008, 3.)

FIGURE 7. Houseware products made from polypropylene with 50 percent pine fiber. (Kupilka 2011.)

Natural fibers available from animal resources are produced by animals or are taken from their skin, bone or hair. All these materials are formed from fibrous proteins such as, keratin collagen and elastin. Silk produced by many insect and spider species has outstanding stiffness and strength and is used in highly demanding applications. Keratin from feathers and wool could perhaps be used as protein source for eco-friendly fiber, but low wet strength limits the possibility to be used in applications that come to contact with water. (Kalia 2011, 5.)

Plant fibers are obtained from various parts of different plants that include bast, leaf, seed and fruit fibers. Bast consists of a wood core with a stem surrounding it and is derived for example from hemp and jute. Leaf fibers are coarser than bast fibers and are most commonly derived from sisal, banana and abaca leaves. Seed fibers include cotton, coir and oil palm. Agricultural residues provide possible sources for plant fibers such as rice hulls and sun flower seed hulls. Properties between different fibers vary a lot depending on the fiber size, structure, source and growing conditions. Important plant fibers are listed in Table 2. (Kalia 2011, 5.)

TABLE 2. List of important plant fibers and their origins. (Kalia 2011, 7.)

Fibre source	Origin
Abaca	Leaf
Bagasse	Grass
Bamboo	Grass
Banana	Stem
Coir	Fruit
Cotton	Seed
Curaua	Leaf
Date palm	Leaf
Flax	Stem
Hemp	Stem
Henequen	Leaf
Isora	Stem
Jute	Stem
Kapok	Fruit
Kenaf	Stem
Oil palm	Fruit
Piassava	Leaf
Pineapple	Leaf
Ramie	Stem
Sisal	Leaf
Sponge gourd	Fruit
Straw (Cereal)	Stalk
Sun hemp	Stem
Wood	Stem

Basic material for all plant fibers is cellulose and its structure determines many of the chemical and physical properties of the fibers. Different plants provide different types of, which each have their own cell geometry. Each natural fiber is composite material where soft lignin and hemicellulose function as matrix material and rigid cellulose as reinforcement. Figure 8 presents injection molded items made from UPM's composite material, which is polypropylene with 40 percent cellulose fiber. (Kalia 2011, 11.)

FIGURE 8. Samples made from UPM ForMi combining polypropylene with 40 percent cellulose fibers. (the logo in the mold is incorrect)

The way to dispose natural fiber composites depends mostly on the matrix material being used. In most cases the material can be burned to generate heat and power. By choosing some biodegradable bioplastic as a matrix material more options for disposal are available since the fiber and the plastic both can be composted. Composite materials can also be re-ground and used again. To maintain the quality level of the product, recycled material should only be used in small portions because, just like conventional plastics, natural fiber composites lose some of their mechanical properties when used again. Recycled material is best suited for applications that have a rather low standard for quality. (Harri Kosonen UPM 2011.)

There are a few challenges and concerns when using natural fiber composites. The most important concern is that the surface of the finished product varies a lot so that manufacturing products with exactly the same appearance is rather challenging. When using cellulose as reinforcement, fibers on the surface of the injection molded product are not as visible as when using other natural fibers. Water absorption of some fibers is also a problem since it affects the bonding between the fibers and matrix. Water absorption can be reduced with physical and chemical modification of plant fibers, using adhesion promoters and in some cases coatings. (Thomas, Pothan 2008, 10.)

3 WAYS TO EVALUATE SUSTAINABILITY

Two ways to evaluate sustainability are covered in this chapter since they are the ones that are the most commonly used for evaluating plastic materials. The first one, the USDA labeling system, only measures bio-based content of the product. The second one, life cycle analysis, is more inclusive and takes more aspects into account.

3.1 USDA label

USDA labels are given by the United States Department of Agriculture and are the result of the BioPreferred program. The program is a voluntary labeling program that measures the bio-based content of a wide variety of products. An example of a USDA label to be used with a product that has at least 57 percent bio-based content is presented in Figure 9. The USDA has established minimum bio-based content standards for many product categories. Every category has its minimum bio-based content percentage that the product must meet or exceed. For some categories, bio-based content standards have not been established, so the decision was made that products in these categories must contain at least 25 percent bio-based content. (USDA 2011.)

FIGURE 9. USDA label for product that contains at least 57% bio-based content. (USDA 2011.)

All the products that use the label must meet the definition for bio-based products that can be found in Farm security and rural investment act of 2002, also called the 2002 Farm Bill. The 2002 Farm Bill defines bio-based products as follows:

> *Bio-based products are commercial or industrial products (other than food or feed) that are composed in whole, or in significant part, of biological products, renewable agricultural materials (including plant, animal, and marine materials), or forestry materials. (USDA 2011.)*

3.2 Life cycle assessment or LCA

Life cycle assessment is a technique that has been developed for systematically identifying environmental impacts of products and services. Demand to reduce green house gas emissions and tightened environmental regulations have increased interest in LCA within many manufacturing and service sectors. LCA is also commonly used to identify environmental impacts of different plastics and plastic products.

The standard ISO 14040 defines LCA as follows;

> *Compilation and evaluation of the inputs, outputs and potential environmental impacts of a product system throughout its life cycle.*

LCA takes all the stages of a product’s life cycle in to consideration when evaluating its environmental burden. The main stages are extraction of resources, production of materials, product parts and the actual product, product management after it is discarded. (Guinée 2002, 5, 6.)

The base of life cycle assessment is formed by four steps that are also presented in Figure 10.

- Goal and scope definition
- Inventory analysis

- Impact assessment
- Interpretation

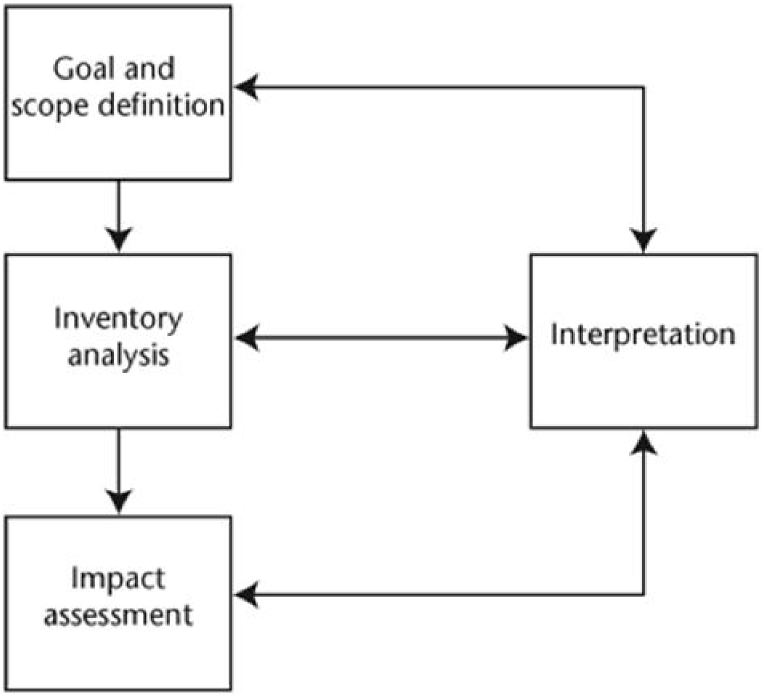


FIGURE 10. Outline of generic life cycle assessment process. (Horne, Grant & Verghese 2009, 3.)

At the first step the purpose, scope, boundaries of the study, the functional units, key assumptions and likely limitation of the work are defined. This is the base of the study that makes comparing of different products possible. The second step includes estimating the use of resources and amount of waste in different stages of the product's life cycle. Usual figures that are presented are raw material and energy consumption, emissions to air and water and solid waste produced. At the step Impact assessment, overall environmental performance of the product is determined. Interpretation is made in every step of the analysis to produce recommendations and conclusions. (Rudnik 2008, 184-185.)

All the aspects of a product's environmental impact are covered, as extraction of different types of resources, different types of land use and emissions of poisonous substances are taken into account. A product in the context of LCA means both physical products and services. When evaluating products with LCA it should be noted that the basis for the comparison is formed by all the functions that products require not the products themselves. Use of the results defines the way how LCA project is implemented. (Guinée 2002, 6.)

LCA is beneficial in many processes and is most commonly used in:

- Investigating the origins of problems that are related to a product
- Comparing improvement variants of a given product
- Comparing the environmental impacts of multiple products
- Designing new products
- Dealing with government policies and business strategies (Guinée 2002, 6.)

3.3 Example LCA studies

The case studies and their results that are described here have been selected on the basis that they relate to similar materials that are evaluated in this thesis. Environmental effects of the original materials used in the case product (polypropylene and PBT) were calculated with SolidWorks 2010 sustainability Xpress tool. The first actual study relates to natural fiber composites, second to cellulose reinforced PP, third to PLA, fourth to bio-based PA, and fifth to bio-PDO based PTT. The results of these studies prove that it is more environmentally friendly to use ecological plastic materials instead of conventional petro-based plastics. It’s possible that manufacturing of material produces hazardous substances such that are presented in Table 4 but this kind of information is not available in all of the cases and therefore the aspect of hazardous substances is not evaluated in this project. Results of these studies are not completely comparable since they are all done by different organizations and therefore there are differences in goal and scope-definitions. To get comparable results, all the materials should be included in the same study and evaluated simultaneously. However, separate studies show that reduction in carbondioxide and/or energy consumptions are achievable depending on the material they are supposed to replace.

3.3.1 Typical materials used in case product

Environmental impact of polypropylene and PBT were calculated with the SolidWorks 2010 Sustainability Xpress tool. Before the report could be printed, rectangle was modeled and the material of the model was changed to PP or PBT. The size of the rectangle was modified so that it would weigh one kilogram. Weight was calculated with the Mass Properties tool. Results of the Sustainability Xpress tool are based on PE international studies. PE International is sustainability software and consulting company that offers strategic a sustainability consulting services. Calculated values for CO_2 emissions and energy consumption can be seen from Figures 11 and 12.

FIGURE 11. Carbon foot print and energy consumption of manufacturing one kilogram of PP.

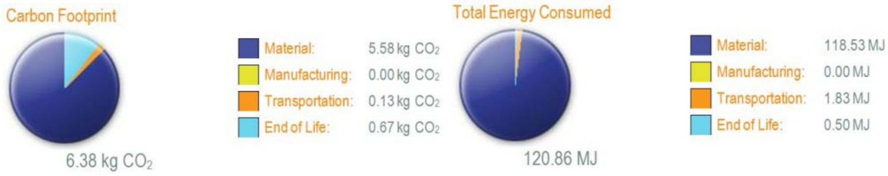


FIGURE 12. Carbon foot print and energy consumption of manufacturing one kilogram of PBT.

An LCA report includes material creation, manufacturing, transportation and end of life disposal. Material creation encompasses raw material obtaining and manufacturing the material. Manufacturing would include environmental effects of all the methods required to manufacture the modeled item, for example injection molding or extrusion. In this case no method was chosen since the study only concentrates on material rather than producing an actual product. Therefore impact of manufacturing in the figures is zero. Transportation includes taking raw materials from the place where they were obtained to a place where the material is made. In this study, Europe was chosen as the manufacturing region. End of life refers to what happens to material when its use comes to an end. Values are determined by typical averages within the use region and that is why these studies are based on certain assumptions. If the results of PP (material creation only) are compared to the results of the study of natural fiber composites against glass fiber composites, presented in Table 4, and VTT's study presented in Figure 13, it can be seen that they are relatively close to each other. Therefore the SolidWorks' tool was considered to be accurate enough source of information.

Actual PP and PBT grades used in case product include glass fiber. By using the results in Table 4 and Figures 11 and 12, estimated environmental impacts of glass fiber reinforced PP and PBT can be calculated. PP is reinforced with 20 percent glass fibers and PBT by 15 percent glass fibers by weight. Compounding fibers to plastic is not noted in the calculations. Estimated impacts for one kilogram of both materials can be seen from Table 3.

TABLE 3. Estimated environmental impact for 20 percent glass fiber reinforced PP and 15 percent glass fiber reinforced PBT.

Estimated environmental impacts of glass fiber reinforced PP and PBT		
	Environmental impact	
Material	CO_2 emissions (kg)	Energy consumption (MJ)
Glass fibers 20% (200g)	0,408	9,666
Glass fibers 15% (150g)	0,306	7,25
PP 80% (800g)	1,576	59,368
PBT 80% (850g)	4,464	94,824
Total PP+20% GF (1kg)	**1,984**	**69,034**
Total PBT+15%GF (1kg)	**4,77**	**102,074**

3.3.2 Natural fiber composites against glass fiber composites

Another LCA study was made by Michigan State University in 2003. Its goal was to investigate if natural fiber composites are environmentally superior to glass fiber composites. The study involved estimating the impact of different fibers and matrix materials on environment and weight reduction achieved with natural fiber composites. Results of the study are presented in Tables 4 and 5.

TABLE 4. Life cycle environmental impact of production of fibers and matrix materials. (Joshi, Drzal, Mohanty, Arora 2003, 374.)

Environmental impact	Glass fiber[a]	China reed fiber[a]	Epoxy resin[b]	ABS[b]	Polypropylene[b]
Energy use (MJ/kg)	48.33	3.64	140.71	95.02	77.19
Carbon di-oxide emissions (kg/kg)	2.04	0.66	5.90	3.10	1.85
CO emissions (g/kg)	0.80	0.44	2.20	3.80	0.72
SO_x emissions (g/kg)	8.79	1.23	19.00	10.00	12.94
NO_x emissions (g/kg)	2.93	1.07	35.00	11.00	9.57
Particulate matter (g/kg)	1.04	0.24	15.0	2.90	1.48
BOD to water (mg/kg)	1.75	0.36	1200	33	33.94
COD to water (mg/kg)	18.81	2.27	51,000	2200	178.92
Nitrates to water(mg/kg)	14.00	24481	1	71	18.78
Phosphates to water (mg/kg)	43.06	233.6	220	120	3.39

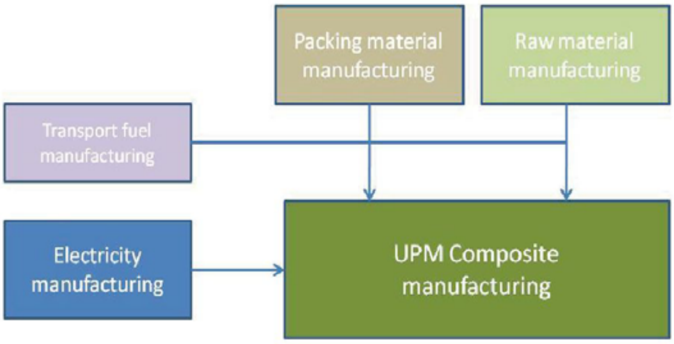
TABLE 5. Weight reduction achieved with natural fiber composites. (Joshi, Drzal, Mohanty, Arora 2003, 375.)

Component	Source study	Conventional composite materials	Weight (g) of reference component	NFR materials	Weight (g) of NFR component	Weight reduction (%)
Auto side panel	[7]	ABS	1125	Hemp-Epoxy	820	27
Auto insulation panel	[5]	Glass Fiber—PP	3500	Hemp—PP	2600	26
Transport pallet	[4]	Glass Fiber—PP	15,000	China reed—PP	11,770	22

The results of this study do not relate to any of the materials that are evaluated in this project. The results were used to estimate environmental impacts of other glass fiber reinforced materials. Use of natural fibers instead of glass fibers results weight reduction in addition to smaller environmental impact. Weight reduction again helps to achieve lower emissions in transportation.

3.3.3 LCA of celluloce reinforced PP

The following LCA study was made by VTT (Technical Research Centre of Finland) and its goal was to measure ForMi's environmental impacts with different cellulose fiber percentages and compare them to acrylonitrile butadiene styrene's (ABS) and unreinforced PP's impact. The study was done by following the ISO 14040 standard. Aspects taken into account in the study and carbon dioxide emissions are presented in Figure 13.



Used plastic and cellulose fibre %	REF 1 ABS, 0%	REF 2 PP, 0%	PP, 20%	PP, 40%	PP, 60%
kg CO_2eq./tonne	3941	2219	1875	1531	1187

FIGURE 13. Aspects taken into account in the VTT's LCA study and results of the study. (Ovaskainen 2011.)

VTT's study only measures carbon dioxide emissions of the chosen materials. Since there is no data available concerning energy consumption or other emissions, it's hard to compare the results with other studies and get a good picture of the total environmental impact. However the study shows that there is reduction in carbon dioxide emissions compared to ABS and regular PP. The amount of reduction depends on the fiber content. In addition, bio-based content increases with the fiber content, which means that less petroleum-based raw materials are needed.

3.3.4 Life cycle assessment of polylactic acid (PLA)

This study can be found in Ewa Rudnik's book called Compostable polymer materials. It analyzes PLA's production system and compares it to the production of some conventional plastics. The study takes following aspects in to account:

- Corn growing
- Transport of corn to the corn wet mill
- Processing of corn dextrose
- Conversion of dextrose into lactic acid
- Conversion of lactic acid into lactide
- Polymerization of lactic acid into polylactide

The results of the study are presented in Table 6. PLA-Year 1 means "traditional" PLA production and PLA-Year 5 means next generation production with lower fossil fuel and raw material consumption. (Rudnik 2008, 186.)

TABLE 6. Environmental impact of production of PLA compared to production of PE-HD, PET and Nylon 6 (PA 6). (Rudnik 2008, 186.)

	Process energy, fossil, GJ/t plastic	Feedstock energy, fossil, GJ/t plastic	Total fossil energy, GJ/t plastic	Fossil CO_2 from process energy, kg/t plastic	CO_2 absorption, plant growth, kg/t plastic	Net CO_2, kg/t PLA*
PLA-Year 1	54	0	54	3450	−2190	1260
PLA- Target. Year 5	7	0	7	520	−2280	−1760
HDPE	31	49	80	1700	0	1700
PET (bottle grade)	38	39	77	4300	0	4300
Nylon 6	81	39	120	5500	0	5500

According to this study, if the target values in total energy consumption and net CO_2 emissions are achievable, PLA has great potential to be a considerably more sustainable alternative for some materials. Today, the manufacturing process itself consumes more energy than HDPEs' or PET's but the use of renewable feedstock compensates for the energy consumption. CO_2 emissions are also higher than HDPE's but it should also be noted that corn absorbs CO_2, which makes net emissions lower than in the rest of the evaluated materials. A downside of using corn as a feedstock is that the same land could be used to produce corn or other crops for the food industry.

3.3.5 Life cycle assessment of bio-based polyamide

EMS is a company that provides many types of plastic materials for a wide range of industries. This lifecycle assessment was done for one of their green line products, PA1010 (XE 4170), which uses castor oil as its feedstock. Assessment is based on the ISO 14000 environmental management standard. The results of the assessment are presented in Figure 14 and Table 7. The assessment takes following aspects into account:

- Castor seed farming
- Castor oil extraction
- Risinoleic acid refining
- Caustic oxidation
- Sebatic acid refining
- Nitrilite process
- Hydrogenation process
- Polymerization
- Compounding
- Packaging

(EMS 2011.)

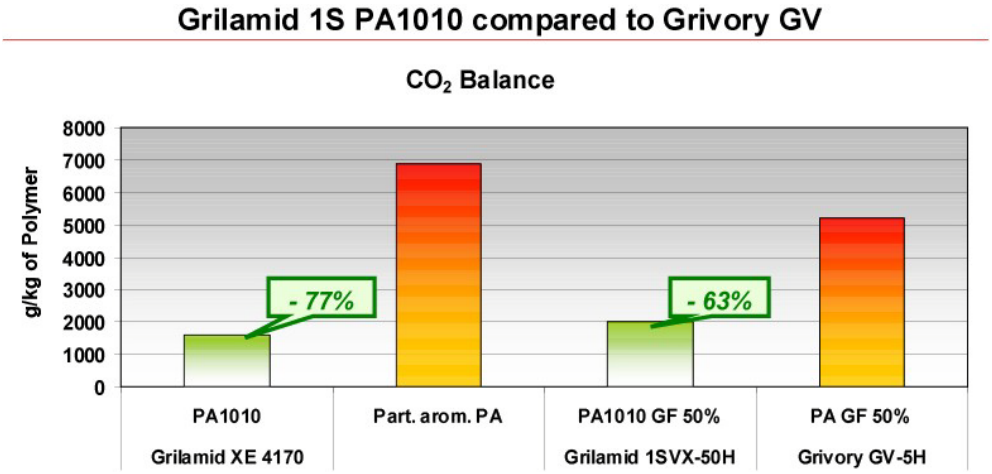


FIGURE 14. Diagram presenting CO_2 emissions of production of unreinforced and reinforced bio-based PA1010 compared to their petro-based equivalents. (EMS 2011.)

TABLE 7. LCA results for unreinforced and reinforced bio-based PA1010compared to their petro-based equivalents. (EMS 2011.)

Grilamid 1S PA1010 compared to Grivory GV

		Base polymer		Compound	
		Grilamid XE 4170 PA1010	Grivory GV PA66 + PA6I/X	Grilamid 1SVX-50H PA1010 50% GF	Grivory GV-5H PA66 + PA6I/X 50%GF
Total Energy	MJ/kg	171	140	114	107
	kg oil/kg equiv.	3.4	2.8	2.3	2.2
CO_2-Balance	g/kg	1'600 (- 77%)	6'900	2'000 (- 63%)	5'200
Land use	m^2/kg	11	-	6	-
Organic content	bio %	98	0	49	0
	non bio %	2	100	1	50
Inorganic content	%	0	0	50	50

EMS's study shows that CO_2 emissions can be reduced significantly by using castor oil as a feedstock. However, these savings can only be achieved when changing material from conventional PA to bio-based. If these results are compared for example to PP's, environmental benefit is smaller. The study does not take into account transportation of castor seeds to the factory, so actual emissions are slightly higher than the study claims. Although the CO_2 emissions are lower, actual manufacturing of bio-based PA requires more energy and oil than conventional PA. Castor plant is not a food crop which grows in semi arid areas so it is not competing for land with food crops. The other benefit of using castor oil as a feedstock is that it replaces petroleum and gives the material renewable content of over 95 percent depending on colors and other additives.

3.3.6 LCA of bio-PDO-based PTT

DuPont published a life cycle assessment study in November 2006 where they compared the production of Sorona to the production of regular PA6. The study was then reviewed externally by Professor Konrad Saur of FiveWinds. FiveWinds is an internationally recognized LCA expert. The results are shown in Figure 15. The study takes following aspects into account:

- Harvesting the corn
- Getting sugar from the corn
- Turning sugar into a monomer
- Turning monomers into polymers

(DuPont 2006.)

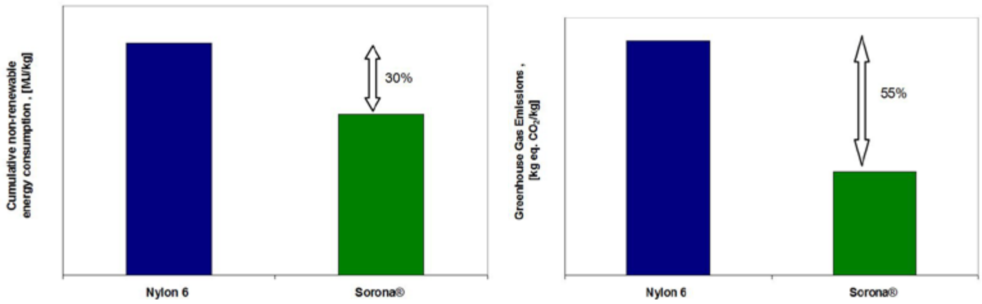


FIGURE 15. Cumulative non-renewable energy consumption and carbondioxide emissions of the Soronas production process compared to ordinary PA6s'. (DuPont 2006.)

DuPont has not published detailed information about the assessment so it is hard to evaluate where the savings in energy consumption and CO_2 emissions come from. The value of non renewable energy consumption is 83.8 MJ/kilogram of material. Actual values of carbon dioxide emissions are 3.38 kilograms CO_2 /one kilogram of Sorona. This value includes bio-based carbon stored in material. (Du-Pont 2006.)

3.4 Comparing the ecological benefits of materials

As stated at the beginning of this chapter, in order to compare these materials accurately, a totally new study would have to be made, where all the same aspects in the production of different materials would be taken into account. Figures in the following table are based on currently available information. Before the results of the different assessments could be compared, the effect of glass fiber was added to the material in those materials in which it was used. For these calculations, values from Table 3 were used in the same way when adding effects of glass fiber to the original materials. Carbon dioxide emissions, energy consumptions and renewable content of two original materials and the materials in the example LCA studies can be seen from Table 8.

TABLE 8. LCA results and renewable content of original and new materials.

LCA results and renewable content for original and new materials			
Material	Environmental impact		Renewable content
	CO_2 emissions (kg/kg)	Energy consumption (MJ/kg)	%
PP+20% GF	1,984	69,035	0
PBT+15%GF	4,770	102,074	0
Bio PDO based PTT+GF	3,179	78,480	31
PP+cellulose	1,531	no data available	40
PLA+GF	1,416	52,866	78
Bio-PA	1,600	171,000	>95

Since there are many values that can be considered to measure environmental impact, it's rather challenging to compare the ecological benefits of different materials. By emphasizing different values, materials can be ranked in many different ways.

If the materials in the table are evaluated only by their renewable content, all the new materials can be considered to be more ecological than the original ones. On the other hand, if energy consumptions in the production processes of materials are compared, for example bio-PA consumes significantly more energy than other materials even though it has over 95 percent renewable content. To make sure that the new material replacing the old one is really more ecological, it should have lower values in all of these three aspects. This leads to a conclusion where PLA is the only material which can replace glass fiber reinforced polypropylene. For glass fiber reinforced PBT there are more options available since all these materials except bio-PA have lower values in all of these figures.

In addition to the figures stated in Table 8, the recyclability of materials should also be compared. In the case of products which contain metal parts tightly attached to them, recycling is hard because plastic and metal should first be separated. In this case recycling plastic waste is limited only to the production process. Currently dark shaded plastic materials are reground and used again in products. Light colored materials go to energy waste, since use of recycled material can easily cause surface flaws in light colors. New materials can be handled in the same way and they are as hard to detach from metal parts. This means that when talking about recycling, there are no environmental benefits or disadvantages when changing the material.

When reaching for a more sustainable production process, possible higher energy consumption in the production process of an actual product should be noted. In this case, possible difference in energy consumption comes from different processing parameters used in injection molding. Higher processing temperatures and pressures mean that more energy is needed.

It is also important to consider how much the changing of the material affects the environmental impact of the whole end product. There would be clearer benefits if the end product contained only plastic.

4 CASE PRODUCT EVALUATION

Due to the confidential reasons, information relating to the case product and its production process can’t be published.

The project started with a search of possible bio-based plastics and natural fiber composites which are claimed to be more ecological than traditional petro-based plastic materials. Most of the materials could be ruled out because of their appearance or lack of required properties. This group of materials was then narrowed down to the most promising ones.

Materials were chosen on the basis of discussions with their manufacturers and/or their suppliers. In these discussions, properties of the available materials were evaluated and the ones considered to be the most suitable were chosen from suppliers' product range. Also material datasheets were examined and injection molded sample pieces were ordered so that visual quality could be evaluated.

4.1 Manufacturing samples

The injection molding machine used for making the samples was typical industry standard hydraulic machine, which had two molds, both with eight cavities, attached to it.

There were two days reserved for manufacturing the samples so there was not enough time to find the best possible processing parameters for each material. The goal was to get good enough samples made so that visual quality could be evaluated and the required test could be done. Parameters were adjusted until the required quality level was achieved. Samples were thrown away until the process stabilized so that all the samples made from the same material would be made with the same parameters.

The tight schedule in sample manufacturing must be taken into account in further evaluation of the samples. Material properties and overall quality of the end product depend partly on parameters used in the manufacturing process. By consuming more time to process optimizing and using other type of equipment, surface quality might improve and mechanical durability might be better. The goal was to follow recommended parameters as closely as possible so that there would not be any major losses in either one.

After the injection molding, the samples were examined visually to make sure that there were not any flows that would cause the sample to be discarded. If the sample passed the examination, it was passed on to a machine that attached the loose halves to each other with a screw.

4.2 Testing

Both of the original materials are well suited for the case product so it was decided that it was enough to use only one of the materials as reference. Polypropylene was chosen as reference because its mechanical and thermal properties and UV-light resistance are weaker than PBT's. If the new materials exceed the results of polypropylenes in the test, they could be considered suitable for case product material no matter what PBT's results would have been.

Testing was done according to agreed requirements. Tests done for defining the quality and performance of other non-plastic parts of the case product were left out since the blades were not under focus. All the materials were put into every test because, even if the material failed in some tests, it might still be suitable for some other application where such property is not needed.

Due to the confidential reasons, descriptions of the test methods and test results cannot be published.

5 COST CALCULATIONS

Even though this project mainly concentrates on evaluating environmental impacts of ecological materials and performance, prices are an important aspect when considering new materials and should be taken into account. This means that even if a new material has better overall performance, a higher price is often a good enough reason to stay with the original material.

This matter was approached by calculating the price of one handle for each material. To get comparable figures, an offer for 5000 kilograms was asked from each material supplier. To get the price of one handle, the weight of sample pieces made from each material was measured and the weight of blades and the screw were subtracted from the total weight. After this the price was calculated using portion. Prices, sample weights, handle weights and handle prices can be seen from Table 9. Because the trade names of the materials can't be published in this context, names in the table are changed.

TABLE 9. Material prices and cost calculations for plastic part of the case product.

Cost calculations				
Material	Material price (€/kg)	Total sample weight (g)	Plastic part weight (g)	Plastic part price (€)
PBT+GF	3,4	83,1	37,0	0,126
PP+GF	1,9	73,3	27,2	0,052
Material 3	1,92	74,3	28,2	0,054
Material 4	3,85	83,8	37,7	0,145
Material 5	15,0	72,8	26,1	0,392
Material 6	9,35	83,6	37,5	0,351

As can be seen from the calculations, all the materials including PBT with 15% glass fibers are more expensive than glass fiber reinforced PP. It should be noted that a higher material price does not necessary mean that the production of the end product is less cost efficient. The material can pay itself back if it has better processability and the production process is faster, meaning that higher volumes of products can be made. This is the case when comparing PP to PBT. To evaluate this aspect thoroughly, more time should be spent to optimize the production process for each material.

Another factor that affects on overall costs of manufacturing the end product is material availability. This means that the material should be available in high enough volumes and it should be manufactured as close as possible to the manufacturing place of the end product. This helps with avoiding unwanted breaks in production and with keeping transportation costs at minimum. All of the tested materials are relatively new and their production volumes are not at the same level as conventionally used materials. At least in the cases of the materials tested in this project, they are only made when ordered and there is no need for maintaining big stocks since the demand for the materials is still low. This means that production has to be planned carefully to make sure there is enough material available. Also longer transportation distances should be noted if a decision is made to use

6 SUMMARY & CONCLUSIONS

Today there are numerous plastic material options available that are marketed as ecological. These plastics include natural fiber composites and bio-based plastics that use renewable sources as their feedstock. Natural fibers can be derived from plant or animal resources and different fibers provide different properties to the new material. Besides mechanical properties, in many cases, natural fibers also change the appearance of the material. The appearance depends on the used fiber type and materials with wood like appearance are available as well as materials that look almost like unreinforced plastics. The ecological benefit of natural fiber composites depends on the amount of fibers used. More fibers mean that less petro-based nonrenewable ingredients are used.

Bio-based plastics can be made by using many different methods and by using many different feedstock materials. The used feedstock and production method define whether the bioplastic is biodegradable or nonbiodegradable. Typically biodegradable bioplastics are made from starch, sugar, cellulose, lignin or plant proteins. Nonbiodegradable bioplastics are most commonly made from plant oils but there are a couple of exceptions like bio-PE and partly bio-based PTT. Using plants as a feedstock slows down the exhaustion of nonrenewable petro-based resources. Plants also bind carbon dioxide, which reduces carbon dioxide emissions when manufacturing these materials. In many cases production also consumes less energy. For these reasons bio-based plastics are more ecological than some conventional plastics. The degree of environmental benefit depends on the material they are compared to. In some cases it is hard to find a clearly more ecological substitute for conventional material.

At the beginning of this project many material suppliers and manufacturers were contacted and asked if they have ecological materials in their product range. If such materials were available, it was discussed with representative of the company, which one they would consider having most potential to be used in houseware applications. After the research possibilities were narrowed down to most promising ones.

When considering replacing the old plastic material with a new more ecological one, the new one should have the right combination of properties, which include as good an appearance as the old material, mechanical, thermal and chemical suitability, environmental benefit compared to old material and reasonable price.

There are at least a couple of ways to evaluate the ecological value of materials. The first one is the renewable content of the material measured in percent. This simply tells how much renewable ingredient a material contains and does not take any other aspects into account. The second method, life cycle assessment or LCA is a more accurate way to compare environmental effects of different materials. The goal of LCA studies is to consider every aspect of the production process of materials and measure at least carbon dioxide emissions and energy consumption in the process. Some studies also include other figures and measure emissions of hazardous substances to water and air.

In this project, both of the methods mentioned, renewable content and LCA studies, were used. Information concerning these aspects was received from material suppliers or manufacturers. The effect of glass fiber was added to the materials in which it was used. Because there was no official data available about PBT's environmental impacts, the SolidWorks sustainable express tool was used. This tool calculates environmental impacts for the chosen material based on assumptions. The accuracy of the tool was checked with PP by first calculating impacts with the tool and then comparing them to values found from other sources.

Overall suitability was evaluated by actually manufacturing case product samples from each material. This made it possible to evaluate appearance in an actual product and carry out typical tests for it. Glass fiber reinforced PP was tested for reference and test results of new materials were compared to PP’s results. Material was considered to fail the test if results were not as good or better. Due to the confidential reasons, test results can’t be published.

Possible further steps of the project could be determining the suitability of the materials for other colors and decoration, optimizing the production process to determine whether the material is as fast to process as the old materials. If the results of the further testing would be favorable, materials could be tested also on other products.

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