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Feasibility Study: Bio-based Biodegradable Thermal Pallet Covers (BBTPC)

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Thermal Pallet Covers provide good passive thermal protection especially during the logistical operation of goods such as higher value perishables, pharmaceuticals, and chemical shipments. Currently, most of the covers are single use, hard to recycle and disposed of landfill. The used covers have caused increasing concerns, resulting in a strengthening of various regulations aimed to reduce the amount of waste generated. The most common thermal pallet cover used today is bubble foil (which is backed aluminum foil, or metalized polyester laminated with the polyethylene bubble wrap). Since, the metallic foil and the polyethylene bubble wrap are laminated together; it is extremely difficult to recycle the product and is virtually impossible to biodegrade. Although, there has been a significant progress in the production of biodegradable materials in recent years, especially biodegradable plastics, their use has not been properly implemented by this industry. The use of bio-based biodegradable materials will unquestionably contribute to the sustainability and lessen other numerous environmental impacts over the whole life cycle of the product due to the use of renewable resources, rather than traditional petroleum based resources. Bio-based biodegradable thermal pallet covers (BBTPC) can make a significant contribution to the recovery of the material, reduction of landfill and utilization of renewable resources. BBTPC are the perfect model of circular economy in which they regenerate CO_2 and use renewable raw material sources for their production. Composting is the most ideal end-of-

life option for any materials instead of landfilling which is the worst disposal option.
The objective of this study is to investigate the possibility of manufacturing biodegradable thermal pallet covers and to study the feasibility of the manufacture, use and disposal of this product.

Keywords	pallet covers, insulation, thermal protection, biodegradation, composting, plastics, cold chain, polylactic acid, circular economy, renewable, bubble foil, bubble wrap, environment, sustainability

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I am solely responsible for any form of errors found in this thesis, regardless of all the support and guidance throughout the project.

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September 2017,
Pradeep Mahat

List of abbreviations

BBTPC	Bio-based Biodegradable Thermal Pallet Cover
EU	European Union
CRT	Control Room Temperature
GARS	Generally Recognized as Safe
FDA	Food and Drug Administration
OD	Optical Density
ASTM	American Society for Testing and Materials
IUPAC	International Union of Pure and Applied Chemistry
ROP	Ring Opening Polymerization
LDPE	Low Density Polyethylene
HDPE	High Density Polyethylene
CAD	Computer Aided Design
WTE	Waste to Energy
MSW	Municipal Solid Waste
BPT	Biodegradable Product Institute
USDA	United States Department of Agriculture
PLA	Polylactic acid
PE	Polyethylene
PP	Polypropylene
PET	Polyethylene Terephthalate
PA	Polyamide
PTT	Polytrimethylene Terephthalate
PCL	Polycaprolactone
PBAT	Polybutyrate
PHA	Polyhydroxyalkanoates
PBS	Polybutylene succinates
PLA/NG	NatureWorks^{TM} PLA next generation
PLA5	NatureWorks^{TM} PLA in 2005
PLA6	NatureWorks^{TM} PLA in 2006
PC	Poly(carbonate)
GPPS	General Purpose Polystyrene
HIPS	High Impact Polystyrene
PETam	PET Amorphous

PETssp	PET Solid State Poly-condensed
PVOH	Poly Vinyl Alcohol
TPS	Thermoplastic Starch
MetPET	Metalized Polyester
MetPLA	Metalized Polylactic Acid
SWOT	Strength Weakness Opportunity and Threat
GMO	Genetically Modified Organisms

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1 Introduction

The urgent need of sustainable alternatives to the petrochemical-based products with the pressurizing regulations and public concerns on ecological issues raise the importance of bio-polymers for the materials production. The vision of this study was to replace the currently used aluminum and petroleum-based plastic materials with a bio-based biodegradable alternative to manufacture a thermal pallet cover for temperature-sensitive products.

The metal foils, plastic bubble wrap used in the thermal pallet cover are practically impossible to recycle and are mostly landfilled. In EU, about 80 million tons of packaging waste is produced each year, covering about one third of municipal solid waste. In which plastic covers 19% of the packaging waste generated, which is 15 million tons, and metals cover 6% of the packaging waste, which is 4.5 million tons. Together plastic and metals cover 25% of total packaging waste generated, which is around 19.5 million tons of waste. There has been an increase in the recycling of the packaging waste in recent years, but the recycling rate of the plastic packaging waste has been very minimal, whereas the metal waste has not been recovered at all by 2013. (Eurostat, 2016, Song et al., 2009) The shares of most common packaging waste in EU are represented in Figure 1.

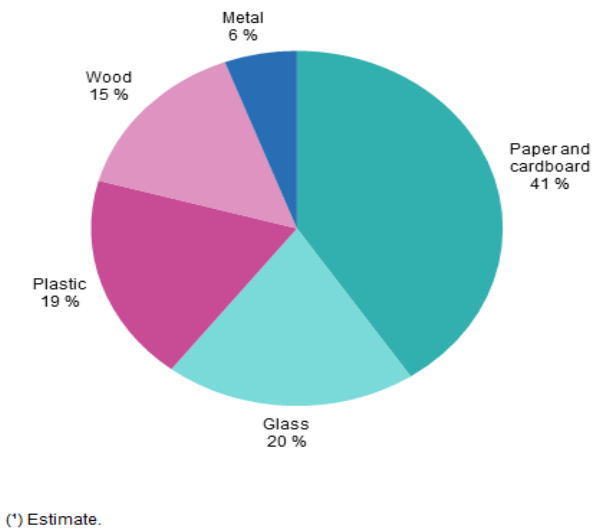


Figure 1. EU packaging waste shares by weight in 2013 (Eurostat, 2016)

It is obvious that waste prevention will eliminate the need of waste management in the first place, which is practically impossible to accomplish. Therefore, waste minimization is most preferable option in dealing with waste which includes reduction and reuse of waste.

When all the waste minimization activities are considered, then we are presented with the waste to manage. Recycling and composting are the best waste management options before energy recovery and disposal to landfill (North London Waste Authority, 2009). The graphics below illustrates the waste management hierarchy listing the most desirable option on the top and least desirable options on the bottom of the pyramid.

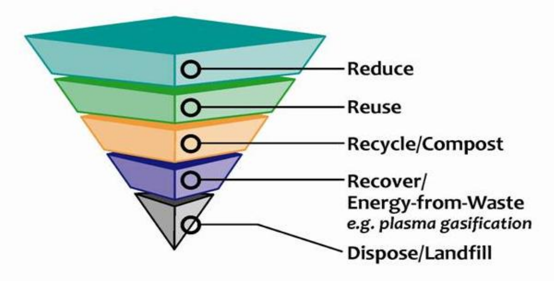


Figure 2. Waste management hierarchy (Schepers, 2011)

The European Commission (2013) obliges the packaging industry to implement greener alternatives in the near future as the 94/62/EC Packaging and Packaging Waste Directive requires the industry to increase the reuse and recycling of waste and to reduce the landfilling of the packaging waste to huge extent by 2030. At the same time, the manufacturing process releases tons of greenhouse gases and uses nonrenewable material resulting in damaging effects on the environment (Jadudova, et al., 2015). Tightening EU requirements and environmental protection were the motivation for studying an alternative environmentally friendly solution for the currently used thermal pallet covers.

2 Background

This thesis was completed for the company TP3 Global Ltd., based in Redditch, United Kingdom. The company has manufacturing and supply bases in America, Europe, Asia and Australia. TP3 Global provides GDP compliant thermal protection for the life sciences and supply chain industries. SilverSkin™ thermal covers are one of the world's leading brand of thermal covers, specially designed to reduce the temperature fluctuation during the thermal peaks and troughs in the supply chain. They are tested, approved and used by many major pharmaceutical, perishables and logistics companies worldwide.

The purpose of this thesis was to study the possibility of environmentally friendly alternatives to the presently used unsustainable thermal covers which are manufactured by using nonrenewable resources and are challenging to recycle and mostly disposed off into the landfill. To this end, a feasibility study was conducted to determine a biodegradable solution for the thermal pallet covers using the existing economically viable materials and technology that match the performance of the current products.

There is a lack of studies on finding and manufacturing a sustainable environmental friendly alternative in this thermal packaging industry even though there has been a substantial improvement in the development of eco-friendly materials and in the technical ability for greener production.

3 Objective of the Study

The main objective of this thesis was to study the feasibility of using a bio-based biodegradable material for manufacturing a BBTPC to protect the temperature-sensitive shipment. The solution presented should match the performance and price of existing thermal pallet covers, proving to be an environmental friendly alternative to the existing pallet covers.

To achieve the above-mentioned objectives, a few sub-objectives were set, which are listed below:

- The investigation should focus on bio-based biodegradable material which has the potential to replace the polyethylene bubble wrap and backed aluminum foil used in the making of a pallet cover offering a complete environmentally friendly solution.
- The materials should be readily available in the market and can be purchased or manufactured easily.
- The manufactured process should utilize the existing technology, equipments and process, with minimum or no changes.
- The product must decompose in industrial composting plant without any side effects and harmful emission to the environment following the composting standards.

4 Statement of a Problem

According to the European Commission (2013), out of 2.5 billion tons of waste generated, 1.6 billion tons were not recovered (reused or recycled). There is a potential of recycling or reusing at least an additional 600 million tons of waste. A total of 31% of the waste was landfilled and 26% was incinerated and only 43% of the waste was recycled. The EU waste economy loses a considerable amount of potential secondary raw materials that can be recovered in the waste streams to build a more circular economy (European Commission, 2013). The following bar diagram shows the current status of the municipal waste treatment in various EU countries in 2013.

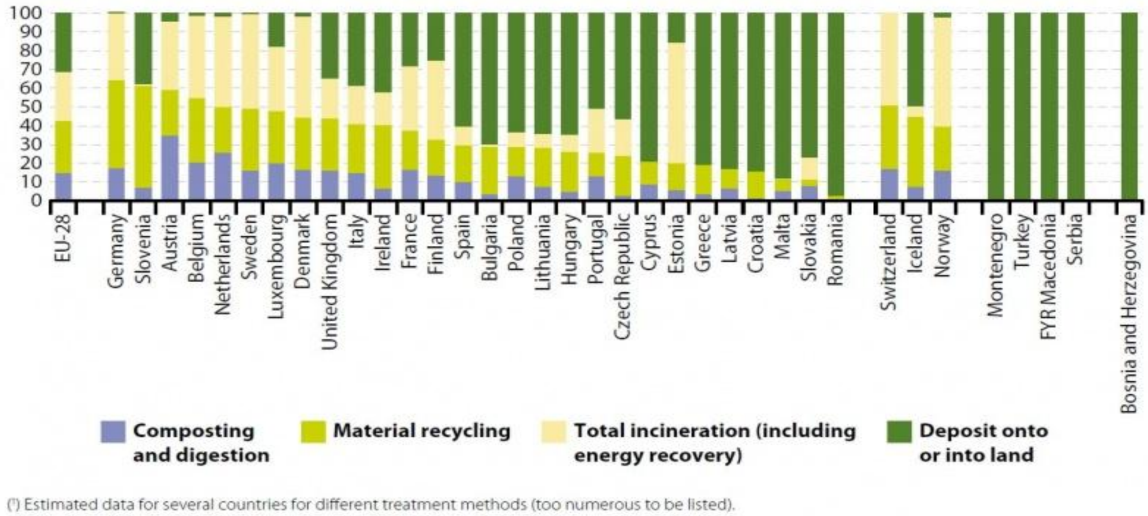


Figure 3. Type of municipal waste treatment method by country in 2013((Eurostat, 2016)

The 94/62/EC Packaging and Packaging waste directive amends to reuse and recycle all the packaging waste by 65% (by weight) no later than 31st December 2025, and by 75% no later than 31st December 2030. In contrast, the directive sets the limit for the landfill waste to 10% by 2030 (European Commission, 2013).

On their weak point analysis of the bubble foil production process, Jadudova, et al. (2015), have discovered that the production of bubble foil consumes significant amount of nonrenewable resources and energy along with the generation of plastic waste, which would eventually have adverse impact on the environment. The analysis also reveals that the most significant category of environmental impact during the production of bubble foil was the consumption of nonrenewable resources, comprising 97% of total environmental impact. Jadudova et al. suggested the necessity of technological improvement and alternative renewable resources for sustainable development decreasing damaging effect on environment.

5 Need of Thermal Protection

Temperature spikes during the supply chain, normally during the loading and offloading of trucks, ships, and aircrafts, during cross docking, and in adverse warehouse conditions. It harms the product integrity and quality. Even though this duration can be very short, normally a few hours, they can be serious threat, especially to the pharmaceutical products. The ambient temperature change experienced during the supply chain while transporting the goods from hot region to cold region can be seen in the figure 4.

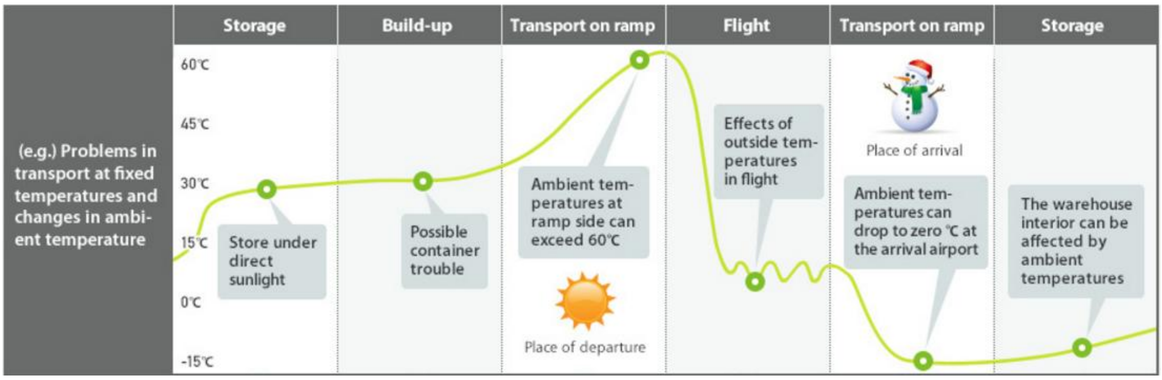


Figure 4. Temperature spikes during the supply chain (Japan Airlines, n.d.)

The *Figure 5* illustrates the temperature threat caused by the distance between the cargo center and the aircraft in the Frankfort airport. The goods from the cargo center (top left) can take hours to tractor the ramp distance of around 6km and on top of that it must wait for the loading process. There is a significant temperature exposure to the product during this period, which could potentially affect the product (TP3 Global, 2017).

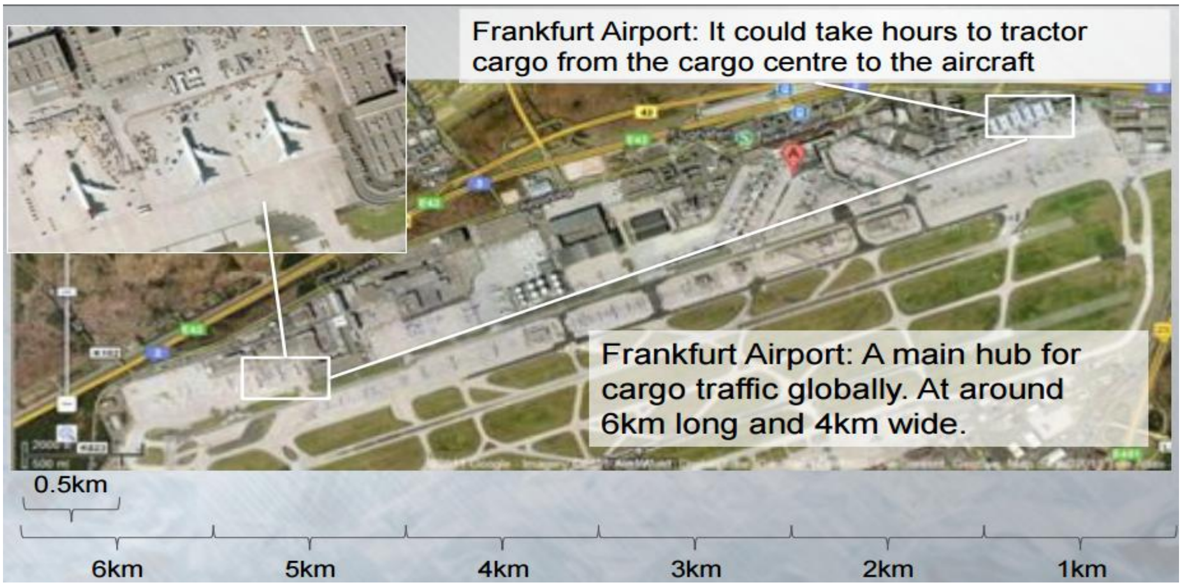


Figure 5. Thermal threat to cargo at Frankfurt airport (TP3 Global, 2017)

Despite of the best systems and monitoring technology during the supply chain, an unplanned delay or rerouting, power failure, unexpected breakdown of refrigeration system can threaten the stability of the shipment temperature, endangering the quality of temperature sensitive products. Sometimes, the final transfer of shipment into the storage facility presents another potential risk, if the timing of the warehouse stage is too early or too late. This situation can lead to the product staying outside for considerable amount of time possibly in the harsh conditions depending on the geographical location (Brown, 2013).

5.1 Cold chain

The term *cold chain logistics* refers to a temperature controlled structure with a series of storage and distribution activities, maintaining the appropriate temperature range for the products without any interruption. It ensures and extends the shelf life of the products such as fresh agricultural products, seafood, frozen food, photographic film, chemicals, and pharmaceutical drugs (Business Wire, 2014).

The term cold chain was established by the food processing and distribution industry, in which ‘cold’ refers to the necessity of continuously controlling the temperature of food products, while ‘chain’ refers to the product chain of custody, where each section is connected to the section before and after. To reduce the risk of microorganisms in the food products, a successful cold chain should maintain the food at proper temperature during the processing, storage, and distribution stage. Every stage from the farm to the consumer is critical for the quality and safety of the food (Germain, 2010).

The compound annual growth rate of global cold chain market is expected to grow at 13.9 percent from 2015 to 2020, and it was valued at $110.20 billion in 2014 and expected to reach $271.9 billion in 2020. In volume, the market stood at 552.09 million cubic meters in 2014. Therefore, there is a substantial need for thermal protection in the Cold Chain (Food Logistics, 2016).

5.2 Perishables

Insufficient temperature protection of the perishable foods during the supply chain results in product safety risk, product quality deterioration, product waste, and product value depreciation (Margeirsson, 2012). It can result in textural degradation, discoloring, bruising, and contamination (bacterial, microbial, and/or fungal growth) which is the related to a public health issue, causing different foodborne illnesses (Rodrigue & Notteboom, 2014). Temperature variation causes irreversible damage to some heat sensitive products like chocolate. High temperature results in sticking of the chocolate to the packaging, whereas low temperature causes cracking of the chocolate surface. To sustain the chocolate quality, it is essential to maintain the temperature in the range of +4°C to +24°C throughout the product life cycle (Moureh, et al., 2002). It is estimated that 20% perishable food loss occurs due to the lack of refrigeration during the supply chain (Brown, 2013; Margeirsson, 2012).

5.3 Pharmaceuticals

A high precaution is extremely essential to protect the pharmaceuticals from the heat and cold challenges especially during the supply chain. As pharmaceuticals are directly related to human health, proper supply chain management is very essential; otherwise it can be ineffective or even harmful to the patients. The external temperature has significant effect on the chemical stability and physical properties of pharmaceuticals. The storage and transportation temperature of the medicinal products has significant effect to sustain the quality of the product throughout the distribution network (HPRA, 2011).
The High external temperature can cause the separation of emulsion systems and sedimentation of active ingredients. It also decreases the active ingredient content through transformation of degraded components like, oxidative, hydrolyzed and other components), In addition to that, it can result in coloration and modification of the product. Some situations may cause medicines to develop toxic properties (Ammann, 2013).

In contrast, the low external temperature can cause crystallization of the components or separation of the components from the fluid medicines (Taylor, 2001). Consequences could be an irreversible change to the active ingredients which lose their healing properties after the product is frozen (Ammann, 2013). The acceptable temperature limits should be maintained, and the special storage conditions specified by the manufacturer should be provided for the good warehousing and distribution practices. A study of temperature excursion during the medicine distribution using a mail-order shipment of medicines via postal service in the USA shows the external temperature as higher as than 60°C during the shipment (Taylor, 2001). To maintain the stability and the proposed shelf life, the medicinal product should be stored as per the conditions described in the label. Some examples of specific storage statements described in the label are listed below:

- Do not store above 25°C or 30°C
- Store below 25°C or, 30°C
- Store in a refrigerator (2°C to 8°C)
- Store and transport refrigerated (2°C to 8°C)
- Store in a freezer (generally the freezer temperature varies from 0°C to -20°C or below -20°C)
- Do not refrigerate/Do not freeze (HPRA, 2011)

Unless indicated otherwise, most of the medicines can be stored in the controlled room temperature (CRT) conditions. The temperature storage indications of such products are 'Do not store above 25°C', 'Do not store above 30°C' and 'Do not refrigerate' (HPRA, 2011). Some product like creams or other biological products does not even require the absolute temperature change; the slight temperature change itself can cause the product to lose their properties (Ammann, 2013).

It is pharmaceutical manufacturers' responsibility to take adequate actions and prepare documentation to guarantee the safety, effectiveness and quality remains as stated in the registration until the final use of the product. They should perform appropriate evaluation with stable data and the possible solution for the potential temperature excursion. It is the manufacturer's obligation to perform a stability study of the product to support storage, handling and transportation and product acceptance after the temperature excursion of the pharmaceuticals (Ammann, 2013).

6 Basics of Thermal Protection

Thermal protection is expressed in two ways: temperature control and temperature protection. A temperature control system is used to keep the product between certain temperature ranges by using active and passive containers for a certain interval of time. Whereas in a temperature protection system, passive equipment acts as a barrier between the products and the ambient conditions that might risk the product temperature. It simply slows down the temperature exchange rather than prevents it. Thermal pallet covers are an example of temperature protection (TP3 Global, 2017).

The effectiveness of thermal pallet cover protection relies on the principles of heat transfer. Heat is a form of energy that transfers from the higher temperature system to the lower temperature system because of the temperature difference. There are three methods of heat transfer: conduction, convection, and radiation.

Conduction is the process of energy transfer via direct contact with the surfaces as a result of interaction between the particles. It can occur in solid, liquid and gas state. Conduction occurs due to the molecular collision and diffusion during the molecules' random motion in gases and liquid state. While, in solid it is because of the combination of vibration and energy transportation by free electrons in the lattice. The rate of heat conduction is determined by the geometry, thermal conductivity, thickness of the object and gradient temperature. The rate of heat transfer via conduction is expressed by the Fourier's law of heat conduction: (Germain & Emond, 2013; Cengel, 2004)

$$\mathbf{Q_{cond} = -kA(dT/dx),}$$

where ***k*** is the thermal conductivity, ***A*** is the area, and ***dT/dx*** is the temperature gradient.

However, convection is the energy transfer between a surface via liquid or gas medium (Germain & Emond, 2013). It comprises of conduction and fluid in motion, which transfer the heat energy. During the process, the solid surface transfers energy to the fluid surface in contact with it by the mechanism of conduction, which is followed by the convection process where energy is transferred from the one end of the fluid to the other with the motion of the fluid molecules. This process removes heat near the solid surface with the cooler fluid molecule. The rate of heat transfer via convection is proportional to the temperature differences and is expressed by the Newton's law of cooling: (Cengel, 2004)

$$\mathbf{Q_{conv} = hA_s(T_s-T_\infty),}$$

where ***h*** is the coefficient of heat transfer via convection in W/m^2.°C, A_s is the surface area where the convection occurs, T_s is the surface temperature, and T_∞ is the fluid temperature on the far side.

Similarly, radiation is the energy transferred in the form of electromagnetic waves which does not require any medium. Various properties determine the process of thermal radiation such as reflectivity, absorptivity depending on the surface of the material and the wavelength which is temperature dependent (Germain & Emond, 2013). The thermal radiation in heat transfer studies is not similar to the electromagnet radiation such as x-rays, gamma rays, radio waves, TV waves and microwaves. The electromagnetic radiation is not related to the temperature of a body however the thermal radiation is caused because of the temperature. Every object which has temperature above absolute zero emits thermal radiation. The thermal radiation emitted from a surface is given by the Stefan-Boltzmann law:

$$\mathbf{Q_{rad} = \varepsilon\sigma A_s T_s^4,}$$

where $\boldsymbol{\varepsilon}$ is the emissivity of the body ranges between 0 and 1 (1 for the black body), $\boldsymbol{\sigma}$ is 5.670 x 10^{-8} W/m^2. $K^{4,}$ $\boldsymbol{A_s}$ is the surface area and $\boldsymbol{T_s}$ is the thermodynamic temperature (Cengel, 2004).

The thermal pallet cover reflects heat radiation, slows down the conduction and blocks the convection of heat across the material.

7 Thermal Pallet Covers

Thermal pallet covers are an insulative reflective material that provides protection against the direct sunlight during the temperature spikes and it also protects against the cold depending on the climatic conditions of the supply route. Basically, it decelerates the temperature exchange between the pallet load and the ambient temperature, acting as a thermal barrier. The reflective thermal pallet covers provides better thermal protection on hot conditions than in cold conditions as its outer reflective layer reflects >95% of radiant heat back to the environment (TP3 Global, 2017).

There are various kinds of thermal pallet covers present in the market. Some of them are listed below:

- Single reflective layer
- Reflective bubble foil
- Multi-laminate foil (multiple layer of material laminated along with the insulation material compressed together)
- Multilayered (mostly foil, polyester wadding and expanded polyethylene loosely bound).

Among the most popular materials used to make thermal pallet covers is reflective bubble foil (TP3 Global, 2017).

7.1 Reflective Bubble Foil

The reflective bubble foil consists of an air bubble wrap sandwiched between the layers of high reflective backed aluminum foil or aluminum coated film. The reflective outer surface has high reflectivity and can reflect the radiant heat from the sun. Most of the reflective bubble foils can reflect more than 95% of the radiant heat received by the surface. The never flowing air trapped inside the air bubbles can slow down the conduction and blocks the convection of heat across the material. (Agrawal Pune, 2016) The working mechanism of the reflective bubble foil insulation material is represented in figure 6 below:

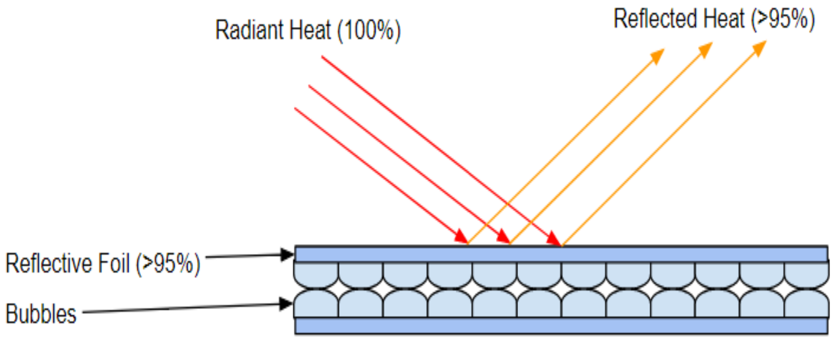


Figure 6. Reflective bubble foil

8 Biodegradation

Biodegradation is the process of changing the materials into natural substances like water, carbon dioxide, and compost by the help of naturally occurring microorganisms. The biodegradation process does not depend on the resources of the material; it depends on the chemical structure of the material. Some bio-based plastics may not be biodegradable, whereas some of the fossil-based plastics can biodegrade. (European Bioplastics, 2017)

8.1 Biodegradable Materials

Materials that can be degraded by living organisms, especially microorganisms are known as Biodegradable materials. The end products are especially water, methane and other possible nontoxic residue like; biomass. Technically, the capacity of the materials to degrade under specific environmental conditions can be specified as biodegradable materials (Mudgal, et al., 2012). Biodegradation is very loose term, which does not require definition of any time limits or conditions. Providing enough time, most materials present in the Earth will eventually biodegrade (Bradley, 2010).

8.2 Compostable Materials

The materials that can be decomposed by living organisms into water, methane, and CO_2 and other possible nontoxic residues under controlled conditions, which can be both industrial and home composting. Technically, everything that is compostable is biodegradable, whereas everything that is biodegradable is not necessarily compostable (Mudgal, et al., 2012). The compostable material should biodegrade within a specified timeframe to be called as compostable, whereas biodegradation does not require any time limits (Bradley, 2010).

Following diagram illustrates the clear picture about technical terms *biodegradability* and *compostability*.

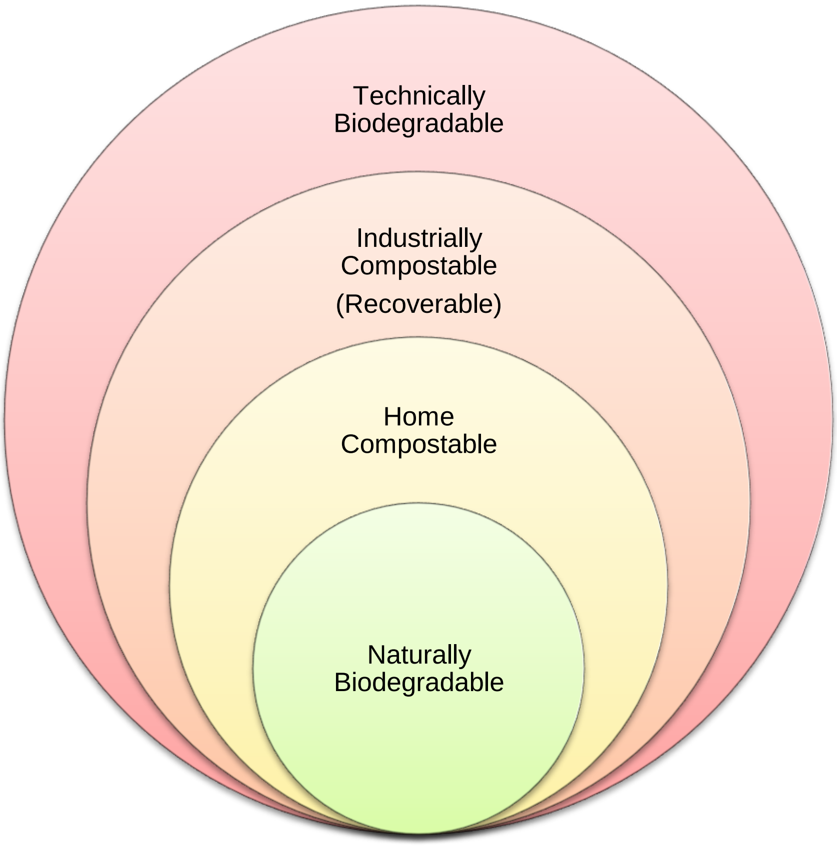


Figure 7. Biodegradability and composability (Mudgal, et al., 2012)

The figure above illustrates that all the materials which are naturally biodegradable, home compostable and industrial compostable can be technically considered as biodegradable materials. Before further discussing the term *biodegradation* for plastics, we need to be clear about some terms in general.

8.3 Bio-plastics and Bio-based Plastics

Bio-plastics consist of many different varieties of materials with various characteristics and applications. A plastic, either bio-based or biodegradable or both bio-based and bio-degradable, are considered as bio-plastics. However, *bio-based bio-plastics* are the plastics that are either fully or partly derived from biomass. Most common biomass used for bio-based bio-plastics are stems from corn, sugarcane, or cellulose (European Bioplastics, 2017).

Some of the example and classification of the different types of plastics presently available are illustrated in the figure below:

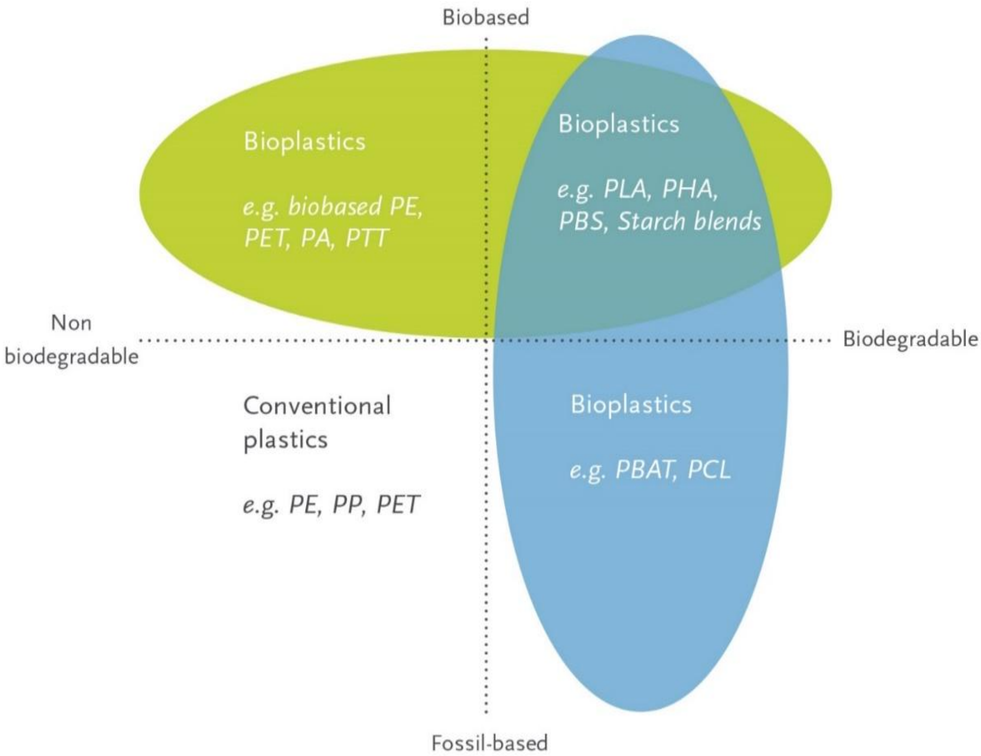


Figure 8. Material coordinates for bioplastics (European Bioplastics, 2017)

PE = Polyethylene
PP = Polypropylene
PET = Polyethylene terephthalate
PA = Polyamide
PTT = Polytrimethylene terephthalate
PCL = Polycaprolactone
PBAT = Polybutyrate
PLA = Polylactic acid
PHA = Polyhydroxyalkanoates
PBS = Polybutylene succinates

Plastics can be classified into two groups: conventional plastics and bio-plastics. The conventional plastics are neither bio-based nor biodegradable, such as PE, PP and PET, whereas the bio-plastic family is further classified into three specific groups:

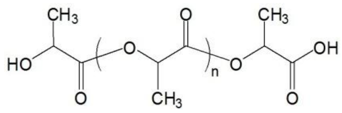
1. Bio-based and biodegradable (e.g. PLA, PBS and PHA)
2. Bio-based and non-biodegradable (e.g. bio-based PE, bio-based PET, PA and PTT)
3. Fossil fuel based and biodegradable (e.g. PBAT and PCL) (Australian Academy of Science, 2015)

Essentially, some 100% petroleum based plastics might be biodegradable, whereas 100% bio-based plastics might not be biodegradable. The chemical structure of the material normally defines biodegradation property of the plastics rather than resources where they are derived from (European Bioplastics, 2017).

9 Polylactic Acid

Polylactic Acid (PLA) is one of the most versatile bio based biodegradable polymers studied extensively in past 20 years. It is very popular because of its low weight, low processing temperature, eco friendliness, less toxicity, and ease of conversion into different form. The production of PLA uses renewable sources like corn, sugar beet, rice, sugarcane, cottonseed, wheat, grapefruit and potatoes (Hu, et al., 2016) (Piemonte, 2012). On top of being bio-based and biodegradable, it also provides several advantages like: carbon dioxide fixation, energy saving, farm economics improvement, manipulative physical and mechanical properties with the help of polymer architecture (orientation, cross linking or plasticization, blending, and branching). The economics and performance of PLA has been improved significantly with the better manufacturing practices and extensive research in this field (Piemonte, 2012).
PLA is colorless to yellow odorless crystals which have following characteristics and properties:

<u>PHYSICAL & CHEMICAL PROPERTIES</u>

Molecular structure:	
IUPAC Name:	2-hydroxypropanoic acid
Molecular Formula:	$C_3H_6O_3$ or $CH_3CHOHCOOH$
Molecular Weight:	90.078 g/mol
Boiling point:	122°C at 15 mm of Hg
Melting Point:	16.8°C
Solid Density:	1.2 g/cm^3 at 21°C

Melt Density: 1.08 -1.12 g/cm^3
Heat of Combustion: 3615 cal/Kg
pH of 10% aqueous solution: 1.75 (National Center for Biotechnology Information, 2016)

MECHANICAL PROPERTIES
Tensile Strength: 55 Mpa
Tensile Yield Strength: 60 Mpa
Tensile Modulus: 3500 Mpa
Tensile elongation: 6.0% (National Center for Biotechnology Information, 2016)

9.1 PLA Production

Polylactic Acid (PLA) is linear aliphatic polyester, which can be either formed by poly-condensation of naturally produced lactic acid or, by the catalytic ring opening of the lactide group. There are two types of poly-condensation process: Direct condensation polymerization and azeotropic dehydration condensation.
An organic acid, 2-hydroxypropinoic acid (LA) produced either by fermentation, or chemical synthesis is the single monomer of PLA. Chemically synthesized LA gives 50% D-isomer and 50% L-isomer mixture. In contrast, bacterial fermentation process produces 99.5% of L-isomer and 0.5% of D-isomers, which allows the production of major stereoisomer using 100% annually renewable resources. Usually, pure L-isomer of LA is used for the production of PLA, with the assistance of lactobacillus genus species such as *Lactobacillus delbrueckii, L. amylophilus, L. bulgarious and L. Leichmanii* for the fermentation process. The process requires the temperature range of 38°C to 48°C, pH range of 5.4 to 6.4 and low concentration of oxygen. (Jamshidian, et al., 2010; Murariu & Dubois, 2016)
There are three possible ways for the polymerization of lactic acid:

- Direct condensation polymerization
- Azeotropic dehydration condensation
- Ring opening polymerization

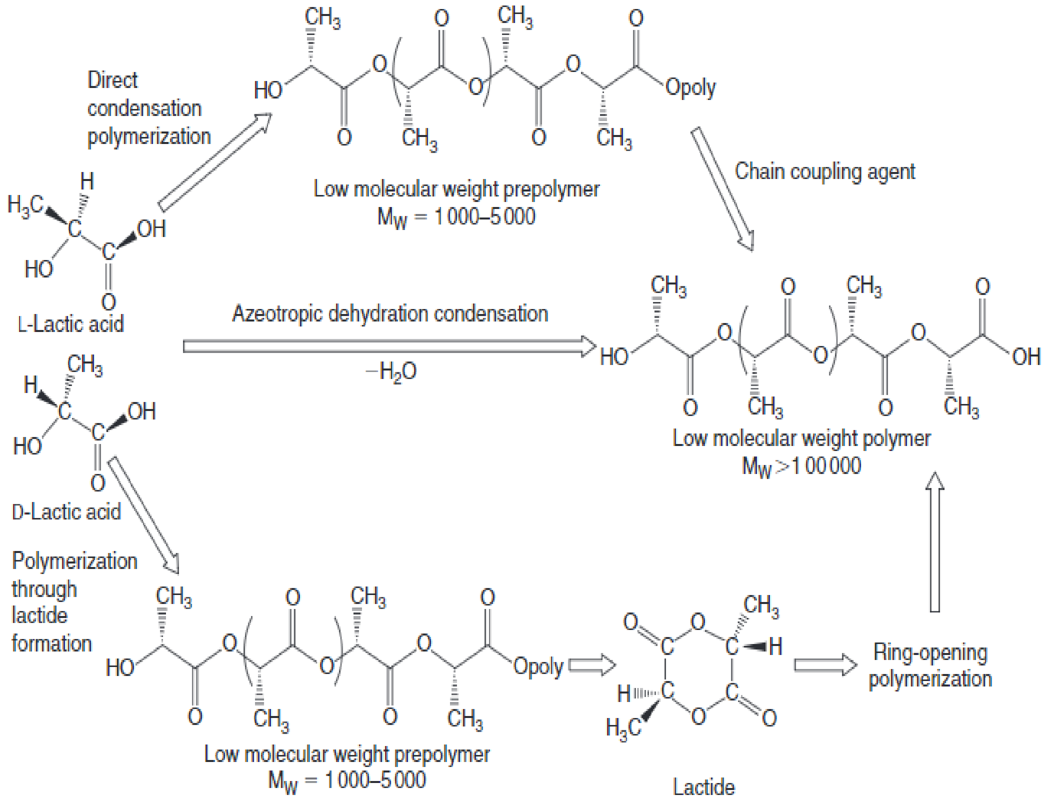


Figure 9. PLA synthesis methods (Kingsland, 2010)

9.1.1 Direct Condensation Polymerization

In direct condensation polymerization, the monomers are introduced to the process of esterification, using solvents and condensation is used to remove excess water under vacuum and high temperature. The molecular weight of the PLA produced with this method is low to medium because of the difficulties in removing the water and impurities, which is not appropriate for the packaging industry. Packaging industry requires high molecular weight polymer. This challenge is overcome by ROP of lactide generally using the stannous octoate (bis 2-ethyl hexanoate, $SnOct_2$) based catalyst (Mudgal, et al., 2012). The PLA manufactured by the direct condensation process are naturally very brittle, but low molecular weight plasticizers, like glycerol, sorbitol and triethyl citrate can be added to overcome the brittleness (Ali shah, et al., 2008). Plasticizers provide the lubrication for the molecules, letting them to be more flexible removing the brittleness of the polymer. Proper ratio of the plasticizer is very essential to obtain the desired property; else excess plasticizer can cause more molecular lubrication, which results in too much elongation, and reduces the tensile strength of the polymer. With the addition of plasticizers to the molecular chain, there is a chance of plasticizers leeching out of the polymers in presence of heat. If the polymers come to contact with the food in this conditions, there is a threat of plasticizers leeching into the food (Kingsland, 2010).

9.1.2 Azeotropic Dehydration Condensation

Unlike the PLA manufactured by direct condensation polymerization, the PLA obtained by using azeotropic dehydration condensation process is of low purity, usually with residual solvents and byproducts in the polymer, which results in solvent waste and pollution (Kingsland, 2010). In this process, generally the lactic acid monomer with the catalyst are azeotropically dehydrated under reduced pressure in the high temperature boiling solvent incapable of donating protons in order to produce PLA with high molecular weight. The excessive amount of catalyst residue in this process may result in degradation and hydrolysis (Piemonte, 2012).

9.1.3 Ring Opening Polymerization

Ring opening polymerization (ROP) is the most preferred method of obtaining high molecular weight PLA. Low molecular weight oligomers or prepolymers are produced in the first step by getting rid of the water in continues condensation reaction of aqueous LA. Then by '*back biting'* reaction using internal transesterification process, the oligomers are catalytically converted to cyclic lactide. This results in the formation of D-lactide, L-Lactide and meso-lactide, among them only D-lactide and L-lactide are optically active. Using the vacuum distillation process, the molten lactide mixture is purified and different grades of PLA are produced with control properties (Murariu & Dubois, 2016).

Basically, the poly-condensation produces PLA with low molecular weight, however ROP provides the opportunity of wider range of molecular weight polymer along with the possibility of controlling the purity of lactide and the polymerization of lactide, eliminating the use of plasticizers (Hu, et al., 2016) (Kingsland, 2010).Polymers obtained from poly-condensation of lactic acid (LA) are usually referred known as poly (lactic acid) and the polymers obtained by ring opening polymerization (ROP) of lactide are known polylactide. In general, the term PLA (Polylactic acid) is used to refer both types of polymers (Murariu & Dubois, 2016).

The largest producer of PLA, NatureWorks LLC, uses multi-step process including ROP of lactide. The process commence with condensation reaction of aqueous LA producing low molecular weight PLA polymer without using any solvents. The polymer is then transferred into lactide stereoisomers with the help of tin catalysis. Meso-lactide is separated after removing the impurities during the distillation stage. Next, Meso-lactide and D-lactide are combined to produce the PLA grades. Furthermore, in the melt with ROP using an organo tin-catalyst, high molecular weight PLA is produced and the residual lactide monomer is separated and recycled after polymerization within the system. This process also eliminates the use of eco-destructive and costly solvents (Murariu & Dubois, 2016).

PLA is classified as GRAS (generally recognized as safe) by the FDA (Food and Drug Administration), USA and is considered safe for all the food packaging applications (Jamshidian, et al., 2010). For food contact applications, Natureworks™ PLA is the most widely used PLA in the world, which is approved for direct contact with all the aqueous, acidic, and fatty foods below 60°C and for acidic drinks served under 90°C. It is also largely used for the packaging of viscous, oily liquids because of its high resistance property to grease and oils (Bradley, 2010).

PLA is fully biodegradable in large scale composting operations with temperature higher than 60°C in presence of certain microorganisms producing CO_2, water, and biomass. Some of the microorganisms responsible for the biodegradation of PLA are *Fusarium moniliforme, Penicillium Roquefort, Amycolatopsis sp., Bacillus brevis and Rhizopus delemer* (Ali shah, et al., 2008). To increase the biodegradability of the PLA, it is generally blended with starch, which also helps in reducing the cost (Ali shah, et al., 2008).

10 Manufacturing Process of BBTPC

10.1 Bubble Wrap Extrusion

There are different types of resins (pellets), a raw material to make the air bubble wrap. For biodegradable bubble wrap, PLA resin was selected. The resins are vacuumed to molding machine, called extruder, at the end of the extruder, the resins are stored in the hopper, which delivers the resins into a long heated barrel, which has temperature between 400ºC to 500ºC to melt the resins and the screw mechanism present in the barrel forwards the molten resin. The heat and pressure forces the melt out through the opening in the stainless steel sheeting die at the end of the barrel to distribute the jelly fluid liquid evenly to form the film with various dimensions. (Mosbergen, 2014; TP3 Global, 2017)

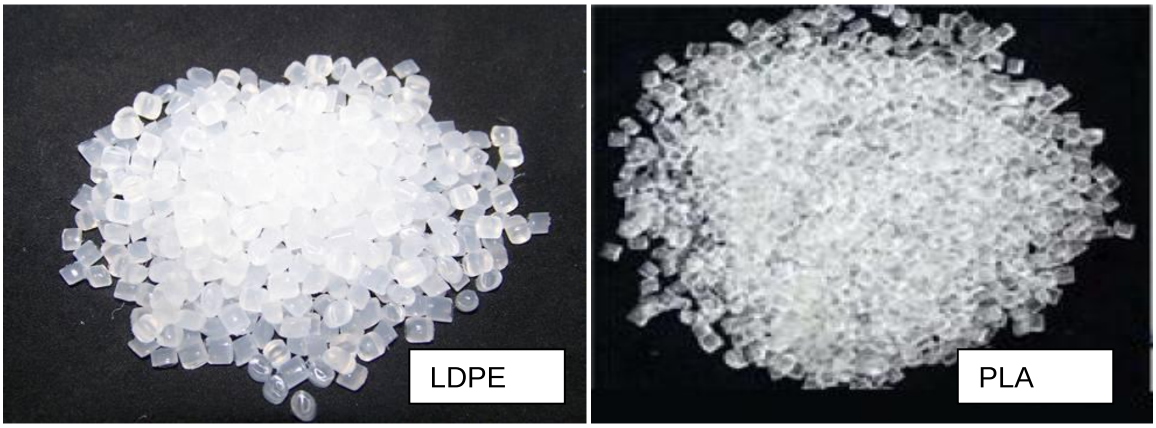


Figure 10. Resins (Alibaba, 2017)

As the jelly fluid is squeezed through the die, it gains a shape of a sheet, which is further carried to the nip (a point where two cylindrical rollers meet) and the motion of rollers move the sheet forward, passing it through the series of the rollers to gain the desire thickness. These rollers are cooled internally with the water which helps to cool the film, maintaining the exact dimension required. After passing through the three roll stack, the sheet enters another series of rollers known as pull rolls, which drag the sheet through rest of the process. (TP3 Global, 2017; Gale Research Inc., 1996; Mosbergen, 2014) Depending on the raw material used, LDPE or PLA Film can me manufactured in this way. To make the film highly reflective, the film metallization process is carried out to vacuum spray the film with aluminum or SiO_2 coating. This film metallization process will be discussed later in Paragraph 10.2.

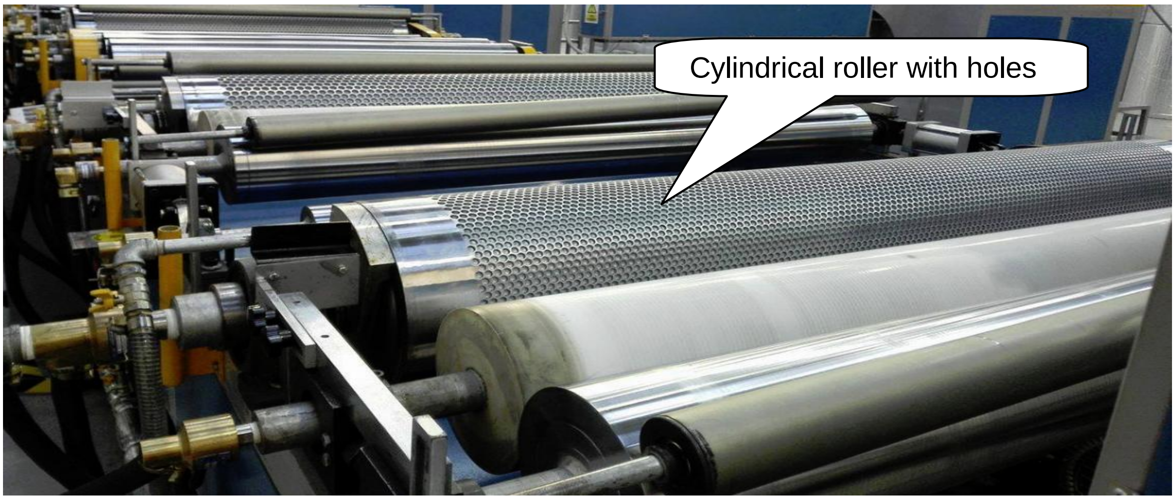


Figure 11. Rollers (Courtesy of TP3 Global Ltd.)

To manufacture the following film is rolled to a cylinder consisting of little holes (Figure 11) which apply suction to vacuum the film down to the holes and another layer of film covers the holes from the top, which traps the air to give the bubble shape and the required size. The bubble film is taken to another series of roller, where the bubble film and metalized film fed together with a layer of molten plastic film in between. During this step, the bubble film, molten plastic film, and the metalized foil coming from three different rollers are bonded together, sandwiching the three layers in the nip between two laminating rollers. This process is also known as heat sealing process (Figure 12), as multiple layers of film is sealed together because of hot molten film which binds the layers together. (*TP3 Global, 2017; Gale Research Inc., 1996*)

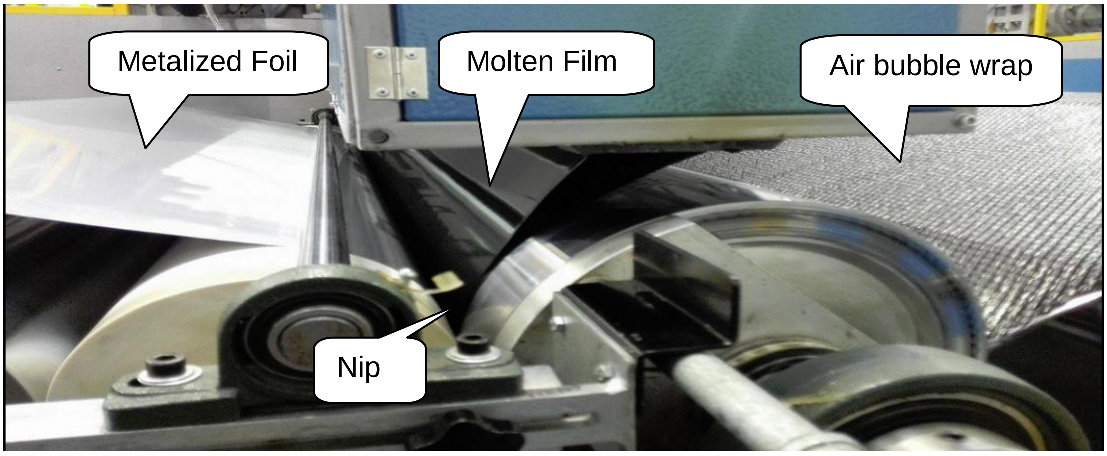


Figure 12. PLA die, metallic foil and air bubble sandwiched between the nip (Courtesy of TP3 Global Ltd.)

Finally, with the help of multiple guide rollers, the final product (bubble foil) is pulled towards the winder roller at the end of the extrusion setup. The film winder generally consists of metal tube or a cardboard core, which is turned by the winder making a big roll of the material. In this way, we can get a bubble foil roll (Figure 13) at the end of the extrusion process.

Figure 13. Bubble foil roll and finished commercial products respectively (Courtesy of TP3 Global Ltd.)

The bubble foil roll goes through a quality inspection process and taken to the warehouse, where it can be changed to any shape, size and required such carry bags, drum covers, cardboard box liners and covers, air cargo inner and outer. The most popular product used commercially is the pallet cover.

10.2 Film Metallization

In a vacuum chamber, which is at approximate $1x10^{-3}$ mbar pressure, aluminum wire is fed onto the heated ceramics, which is at approximately 1100ºC temperature. The temperature is hot enough to turn the solid metal into vapour. Then PLA film is run through the cloud of aluminum, which is formed because of the extreme temperature. The aluminum vapour condenses back to a solid on contact with the cooled film and forms a solid coating. The Optical Density (OD) can be adjusted for the silver/shiny effect required for the higher reflectivity of the surface, the OD is usually around 2.0 - 2.5 OD for the normal reflective foils used to prepare the thermal pallet covers. To adjust the OD, either the wire feed rate can be adjusted, or film winding speed can be altered. Both feed rate and winding speed can be adjusted as per the requirement (Stott, 2017).

Generally, the aluminum coating present in the surface of PLA is too thin (approx. 40 nm or less) to have influence on the biodegradation process. The remains, has very little impact on the environment and the film can biodegrade, leaving the aluminum behind. Modification of the PLA films with vacuum coated aluminum and silicon oxide does not affect final time of polymer disintegration (Krasowska, n.d.) (Stott, 2017).

To market any product as biodegradable, a certain percentage of the product must be made of biodegradable materials. Biodegradable packaging is made up of many substances which are not biodegradable, such as; ink, adhesive, heat seal coatings, aluminum. As long as the percentage quotas for the standard are met, the product can be classified as biodegradable product (Stott, 2017). Metalized PLA has been verified as biodegradable in composting conditions as per ASTM D5338 test method and D6400 standard, which required 90% degradation of the product in 180 days, without the addition of toxicity to the soil. (Krasowska, nd; Stott, 2017; Tolinski 2012)

10.3 Making of Pallet Cover

First of all, the bubble foil roll is cut into various shapes and sizes with a help of CAD cutting equipment. Computer Aided Design (CAD) cutting equipment consists of motion control high precision knife cutter which takes command from the predesigned CAD software nesting well defined shape and dimensions. This process maximizes efficiency by increasing speed, accuracy and the material use and minimizes the material waste (CAD Cut, 2017). The CAD equipment cuts the material to the dimensions required for the top and bottom section of the material, making it easier to fold it up in the pallet jigs to give it a pallet shape.

Figure 14. CAD Cutting Equipment (Jingwei Systemtechnik Ltd., 2014; TP3 Global, 2017)

The folded material is either heat sealed using a heat sealing machine or, taped with double sided tape in the joints to seal it. The seams are further taped from outside with pressure sensitive sealing tape to improve the thermal efficiency blocking the thermal bridge formed in the joints. This can be done with company trademark name printed tape to provide brand identity and professional look.

10.4 Instructions for Using Thermal Pallet Cover

Thermal pallet covers mainly consist of two configurations: ‘top-only’ and ‘top and base’ configuration. It is estimated that the use of a base provides approximately 10% improvement of thermal performance of the pallet cover, because it fully encloses the product. For operational convenience, mainly two types of base are used: flat base for the preformed pallet (fork lift truck operation) and pre-formed base for building the pallets by hand. The use instructions for the thermal pallet cover are explained below;

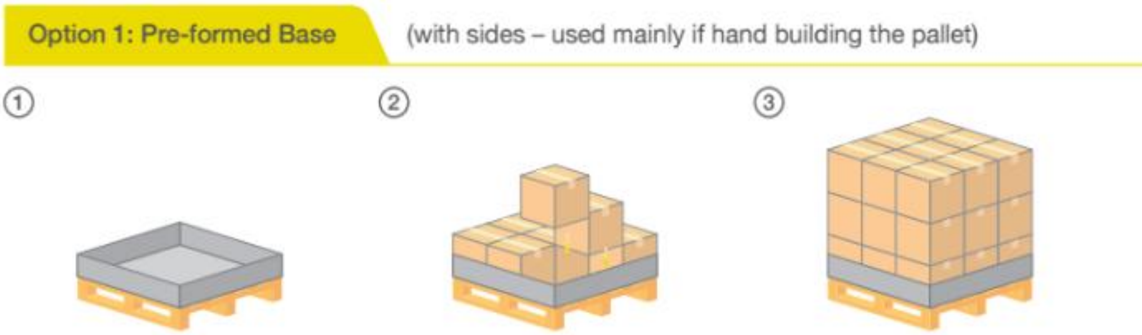


Figure 15. Pre-formed base

For hand building the pallet, first the base is placed above the pallet and the product is stacked on top of it as shown as in the figure above.

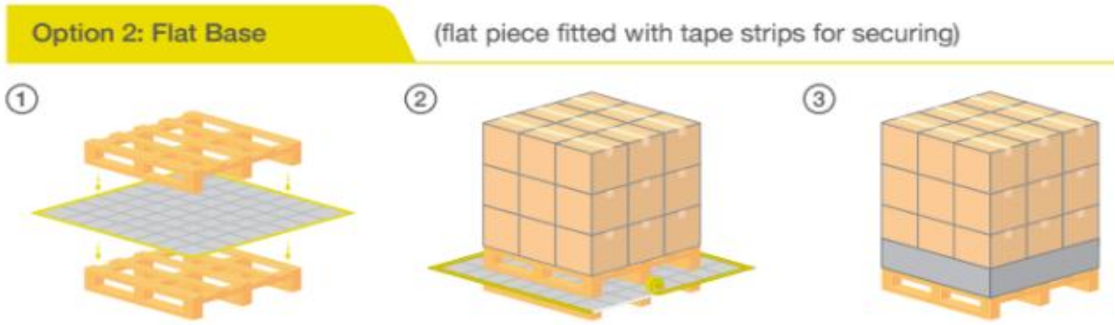
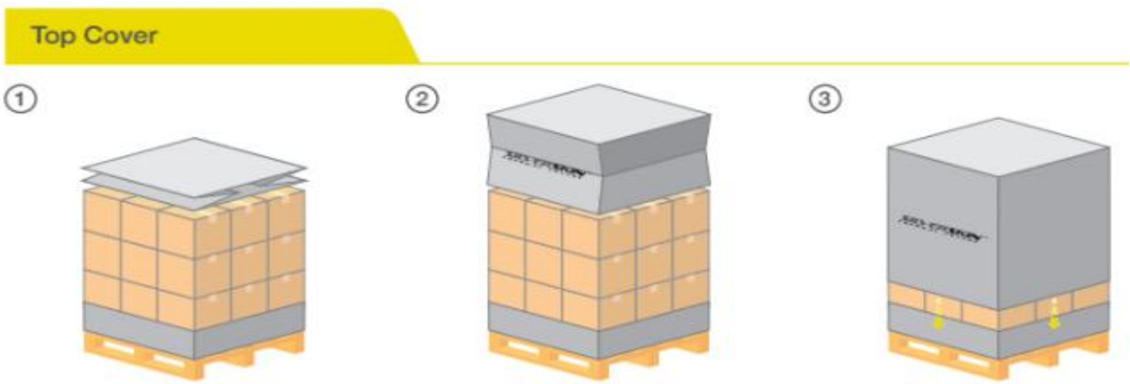


Figure 16. Flat base

To operate the pre stacked pallet with the help of fork lift truck, the configuration demonstrate above is used. First the flat base is placed over the pallet and then previously palletized product is placed on top of the flat base. The base is then folded up and taped as shown as in Figure 16 above.



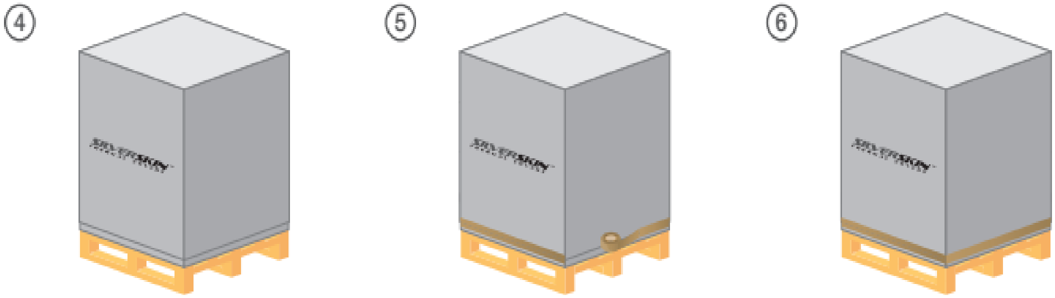


Figure 17. Top cover using instruction

Next, the top cover is placed over the top of the load and slid down. The top cover overlaps with the base and it is sealed with the help of standard warehouse tape or shrink wrap at the very bottom to secure the cover to the pallet. The graphical representation of putting the top cover and sealing is illustrated in Figure 17 above.

11 End of Life options for BBTPC

With proper planning and careful development of vision for the product lifecycle including end of life options, the environmental impact of the product can be maintained at insignificant level. The waste hierarchy encourages capitalizing on the functional performance using minimum resource thus supplying ecological and economical service to the people. PLA products have more ends of life possibilities than other plastic products and they are briefly discussed in the following paragraphs.

11.1 Reuse and Recycling

It is always wise to consider multiple reusing and recycling the product before disposing. Reusing is the most preferred end of life option for any products, which eliminate the generation of waste in first place. It is obvious that reusing any product will save money, raw materials and energy required for the manufacturing and transportation along with the reduction of emissions and volume of landfill waste (Rose, 2017).

Recycling PLA products allows us to reuse the material itself and the embedded energy stored in the material which would be lost during the composting (O'Connor, 2011). For recycling, several facilities are present in different locations, where mostly the chemical process used by other several plastic industries known as hydrolysis is used. During the process of hydrolysis, PLA is broken down into its lactic acid form and then lactic acid can be upgraded once again to PLA resin for further use (Nature Works, 2017). The recycled PLA can be of same quality as it is claimed to have no down recycling (Loopla Galactic, 2009). Infra-red automatic sorting equipment is the most used method for the sorting of PLA plastics (Bradley, 2010). To achieve the best recycling results, the use of best available technologies for collection, sorting and processing is very essential (Nature Works, 2017).

At present, there are only two PLA recycling facilities in the world: Plarco Inc. in Wisconsin, USA, and another in Loopla Galactic in Belgium (Business Wire, 2010; Loopla Galactic, 2009). In the same way, BioCor LLC is a company that buys post-consumer and postindustrial PLA product waste and sends it back to recycling facilities to produce recycled PLA resin (Niaunakis, 2013).

11.2 Incineration

Incineration is globally used end of life option for various materials. Generally, waste to energy (WTE) incineration facilities are used to burn municipal solid waste or refuse derived fuel to recover energy (Nature Works, 2017). It is the process of oxidation of the waste with the objective to reduce the volume and hazard, destroying or capturing the possible harmful elements. It also offers the means of recovering the waste energy to useful energy as well as recovering chemical contents from the waste (European Commission, 2006). The efficiency and effectiveness of the incineration process depends mainly on the energy values of the materials used in the WTE facilities (Nature Works, 2017). To help to understand the energy values of most common materials, they have been compiled in Table 1 below:

Table 1. Energy value comparison of various materials (Nature Works, 2017)

Materials	Energy Values (BTU/lb)
Fuel Oil	20,900
HDPE	18,700
Rubber & Leather	12,800
PET	10,900

Wyoming coal	9,600
Textiles	9,400
PLA	8,368
Newspaper	8,000
Wood	7,300
Corrugated Boxes(Paper)	7,000
Average MSW	5,900
Yard Waste	2,900
Food Waste	2,900

The heat content of PLA is higher than other cellulosic based materials and average municipal solid waste. The burning of PLA does not emit any volatiles and other low residues (Nature Works, 2017). Even though, incinerating the PLA releases carbon dioxide, it can theoretically be considered as a carbon neutral event as the carbon present in the PLA was previously an atmospheric carbon. On the other hand, the use of other energy source for the production and the use of fertilizers to produce raw materials for the PLA productions makes it a net carbon positive effect, but the effect is less than one third of CO_2 impact of other traditional plastic resigns like PET (Tolinski, 2012).

11.3 Landfill

In spite of being the most terrible end of life option, the landfill is the most common waste disposal method in most part of the world including many EU countries regardless of the effort from EU to reduce landfilling (European Bioplastics, 2017). We should always try to eliminate this option in any product's end life, but it is still better than other plastic products because PLA contributes less to greenhouse gas and use minimum nonrenewable energy source during their life cycle. They are stable in the landfills with no statistically significant amount of methane released (Nature Works, 2017). The PLA product will require specific conditions, such as pressure and temperature, to biodegrade, which could be only managed in industrial composting facilities. Hence, it stays in typical landfills for a very long period of time (Mendizabal, 2015)

11.4 Biodegradation / Composting

The biodegradation of the PLA consists of 2 steps. First, the polymer chains are split apart because of the heat and moisture present in the compost pile. This process creates smaller polymers, which are then further split down to lactic acid. The lactic acid and other reduced polymer remains are then consumed as nutrient by the microbes present in the compost and soil, resulting carbon dioxide, water, and humus (a soil nutrient) as an end result (Nature Works, 2017). The complete biodegradation of PLA products only takes place in the industrial composting facilities under controlled temperature and pressure.

11.4.1 Industrial Composting

The industrial composting process proceeds in two different phases: active composting, which is also known as rotting and followed by curing, which is also known as post rotting. The type of composting determines the duration of the active composting. Microorganisms (*mesophiles*) grow on the organic waste, using it as source of nutrients and energy, under the normal composting conditions. The microbial populations present in the organic waste break down the waste into CO_2, water, and heat, which is released to the environment.

Organic waste is accumulated as piles during composing which results in the increase of temperatures within the pile. The *mesophiles* stop their activity or die because of the increase in temperature and are replaced by thermophiles. *Thermophiles* are the microbes adapted to live at high temperatures. The temperature of the industrial composting heaps usually range between 50°C to 60°C. During the curing phase, the decomposition rate becomes slow and steady and maturity of compost takes places at the lower mesophilic temperature (<40°C) with the synthesis of humic substances (European Bioplastics, 2015).

PLA Products are completely biodegradable in a large scale industrial composting plant under a controlled temperature of 60°C and above. PLA degrades with the process of hydrolysis into water soluble compounds and lactic acid within first two weeks during the initial stage of the process. After that these products are metabolized into CO_2, water and biomass with the help of various microorganisms such as *Fusarium moniliforme,* *Penicillium Roqefort, Amycolatopsis sp.,Bacillus brevis and Rhizopus delemer* (Ali shah, et al., 2008).

Even though the definition of the industrial composting varies across the regions as per their standards and legislations like EN13432 for Europe, ASTM D6400 (plastic films and bags) and ASTM D6868 (packaging) for the US, a material which meets the following criteria can generally be called as industrially compostable material:

- ***Chemical characteristics***: It contains at least 50% organic matter (based on dry weight) and does not exceed a given concentration for some heavy metals.
- ***Biodegradation***: It biodegrades at least by 90 %(by weight) within six months under controlled composting conditions (temperature of 50+/- 2°C)
- ***Disintegration***: It fragments into pieces smaller than 2mm under controlled composting conditions within 12 weeks
- ***Eco-toxicity***: The compost obtained at the end of the process does not cause any negative effects (which could be measured, for example by the effect on germination and growth of plants) in the environment (World Economic Forum; Ellen MacArthur Foundation; McKinsey & Company, 2016)

Due to the increasing environmental awareness, there are many industrial composting facilities around the world. Centralized composting is inexpensive method and the output is especially used as the fertilizer for landscape maintenance, forestry, and agriculture.

11.4.2 Composting Plants Accessibility

In UK, there were 203 composting sites in 2012 and they are mainly located 38 in the east of England, 35 in south east, followed by 27 sites in the North West (Themelis & Bourtsalas, 2013). On the other hand, a recent research by BDS Marketing Research (2016) suggests that there are 230 active composting operations in Great Britain, run by 200 different organization.

According to the research conducted by Bionova (2009), there are in total 222 working composting plants in Finland. There are some plants which would be starting soon along with more other planned composting facilities. Among 222 composting plants there are 13 units with the capacity of around 30,000 t/a, 74 units within the scale of 2,000 to 30,000 t/a, and 135 composting plants with the capacity around 2,000 t/a (Bionova, 2009). Some of the largest composting plants are tabulated below:

Table 2. Largest composting plants in Finland (Bionova, 2009)

S.N.	Company / Organization	Location	Capacity (1000 t/a)
1	Helsingin Vesi	Sipoo	91
2	Mustankorkea Oy	Jyväskylä	74
3	Pirkanmaan Jätehuolto Oy, Koukkujärvi	Nokia	60
4	Biolan Oy	Eura	55
5	Envor Biotech Oy	Forssa	55
6	Pirkanmaan Jätehuolto Oy, Tarastenjärvi	Tampere	50
7	Helsinki Metropolitan Area Council	Espoo	49
8	Kujalan Komposti Oy	Lahti	45
9	Koillis-Savon Ympärisöhuolto Oy	Juankoski	38
10	Humuspehtoori Oy	Pälkäne	37
11	Pirkanmaan Jätehuolto Oy	Tampere	35
12	Vapo Oy biotech	Joutseno	34
12	Stormossen Oy	Mustasaari	32

12 Environmental Certification

Manufacturing a sustainable product is not sufficient for the ecological life cycle of product. Most of the biodegradable products are designed to be alternatives for the regular traditional products; therefore, it is very essential for the identification and separation of environmentally harmful product from green products. This is only possible with proper environmental certification and labels. Final product has to go under the compostable test following the officially recognized standards to be certified as compostable product. Regardless of raw material use of various parts used for the production of the product, the final product always has to go under the compostable test following the officially recognized standards to be certified as a compostable product (Horvat & Kržan, 2012).

Environmental certification is very important to prevent the contamination of the product and for proper end of life disposal. To certify biodegradability, the product must be decomposable under specified conditions and incase of renewable resources use the product should be certified with indicating specific renewable percentage. ***DIN Certco*** and ***Vincotte*** are most recognized environmental certification organization in Europe and ***Biodegradable Product Institute (BPI)*** is responsible for the environmental certification in US for the biodegradable and bio-based polymers (Horvat & Kržan, 2012).

Vincotte certifies the products as "***OK biobased"*** certification with the stars indicating four different percentage of bio-based percentage (renewable material percentage) in the product. The products are classified into 1 star-bio-based, 2 star-bio-based, 3 star-bio-based and 4 star-bio-based in regards of the renewable material composition percentage respectively (Vincotte, 2017). The certification logos with their respective bio-based percentage are is illustrated below:

(20 - 40)% Bio-based	(40 – 60)% Bio-based	(60 – 80)% Bio-based	> 80 % Bio-based

Figure 18. 'OK biobased' certificate labels (Vincotte, 2017)

In the same way, the German Institute of Standardization ***'DIN Certco'*** also provides certification schemes for the bio-based products with three different bio-based percentage classifications which are listed below:

(20 - 50)% Bio-based	(80 – 85)% Bio-based	> 85 % Bio-based

Figure 19. 'DIN Certco' certificate labels

Vincotte also provides the certification for the compostable and naturally biodegradable products which are presented in the Figure 20.

				
Biodegrades completely in industrial com-post systems	Biodegrades completely in home compost systems	Biodegrades completely in soil	Biodegrades Completely in natural fresh water	Biodegrades Completely in sea water

Figure 20. 'OK compost' and 'OK biodegradable' certificate labels

The products marked with 'OK compost' label are assured to be entirely biodegradable in industrial composting plant under the reference of EN 13432: 2000 standard, complying EU Packaging Directive (94/62/EEC). All Vincotte certification is authorized by European Bioplastics and might be awarded with the following *Seedling logo* which is recognizable all over the European market (Vincotte, 2017).

Figure 21. European Bio-plastics Compostable Seedling logo

Correspondingly, BPI and United States Department of Agriculture (USDA) in the United States certifies the industrially compostable product and bio-based product with different compostable logos which are given in Figure 22 (Karaiskou, 2016; Biodegradable Product Institute, 2016):

BPI Industrial Compostable Product	USDA Bio-Based Product

Figure 22. US industrial compostable and Bio/based product logos

13 Environmental Analysis of BBTPC

Most of the major components of our product consists of PLA as a raw material, I will be mainly discussing about environmental analysis of PLA. All the production processes except for the production of raw materials are similar to the production of thermal pallet covers including the metallization of the film; therefore, it is sensible to compare the PLA production with similar polymer production processes. Some of the major environmental concerns like energy consumption, greenhouse gas emission, corn dependency and land use are discussed below:

13.1 Energy Consumption

Even with the existing traditional methods, the production of PLA requires less energy compared to it general alternatives (LDPE and HDPE). LDPE is the most common polymer for the manufacturing of air bubble wrap. We can see that the production of LDPE requires the energy of 81 MJ/kg; however, PLA production only uses 57 MJ/kg for its production. The energy required for synthesizing and manufacturing PLA with other polymers such as LDPE and HDPE are listed in Table 3. The abbreviations used in the Table 3 are explained below the table.

Table 3. Energy required for production of different polymers (Environment Australia, 2002)

Polymer	Energy (MJ/kg)
LDPE	81
PHA-Fermentation process	81

HDPE	80
PCL	77
PVOH	58
PLA	57
TPS + 60% PCL	52
TPS + 52.5% PCL	48
TPS + 15% PVOH	25
TPS	25

Low Density Polyethylene(LDPE)
High Density Polyethylene(HDPE)
Polyhydrooxy Alkanoate(PHA)
Polycaprolactone(PCL)
Poly Vinyl Alcohol(PVOH)
Thermoplastic starch(TPS)

13.2 Greenhouse Gas Emission

PLA is considered direct environmental friendly alternative to petroleum based plastics, especially to PET. The nonrenewable energy use and greenhouse gas emission value of petrochemical PET is 69.4 gigajoules and 2.15 tons of CO_2, whereas for PLA, it is 42 gigajoules and 1.3 tons of CO_2, which is 40% lower than petroleum based PET. On top of that, PLA is 100% compostable and is suitable for multiple ends of life options, while the disposal of PET results in environmental pollution (Xu, et al., 2015).

There are some companies which priorities in greener production of PLA in comparison to earlier production processes using more eco-friendly materials reducing the emission and price. Some ideas includes using agriculture residue and food waste and substituting the energy consumption with solar and wind power energy. These ideas decrease the fossil fuels consumption, corn dependency, reducing air, water and waste emissions to the eco-system. The most positive factor of these types of production idea is reduction of CO_2 emissions which is considered as the major contributor to the climate change and global warming.

Natureworks™ LLC prioritizes in greener production of PLA polymers and they were successful in decreasing the CO_2 eq. /kg emission from 2kg in 2003 to 0.3 in 2006. The CO_2 eq. /kg emission is estimated to decrease to -0.7 kg for their next generation PLA production using wind energy in near future. This means, PLA can become a greenhouse sink rather than emitter of greenhouse gas. The net greenhouse gas emission in CO2 eq. /kg polymer of PLA along with some other commonly used polymers are listed in Figure 23 (Jamshidian, et al., 2010). The abbreviations used in Figure 23 are explained below the figure.

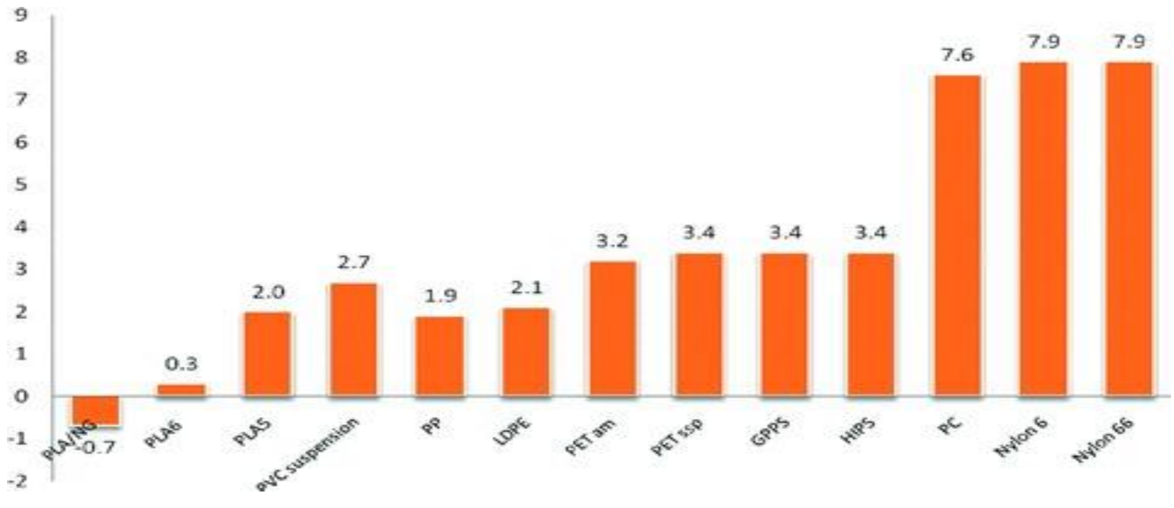


Figure 23. Net greenhouse gas emission of commercial polymers (Jamshidian, et al., 2010)

PLA/NG = NatureWorks™ PLA next generation
PLA5 = NatureWorks™ PLA in 2005
PLA6 = NatureWorks™ PLA in 2006
PC = Poly(carbonate)
GPPS = General Purpose Polystyrene
HIPS = High Impact Polystyrene
PETam = PET Amorphous
PETssp = PET Solid State Poly-condensed

It is clear from the above figure that the PLA production has far less emissions compared to other polymer production processes. There is ongoing research on the production of PLA skipping the use of plants and by converting greenhouse gases like methane and CO_2 directly into lactic acid using microorganisms (Nature Works, 2017). There is a huge potential of PLA production to become a greenhouse gas sink with the negative emission to the environment in the near future (Jamshidian, et al., 2010).

13.3 Corn Dependency and Land use

Corn dependency and land use is another big concern for the production of PLA. It is estimated that, to produce 1 kg of PLA, 2.5 kg of corn is needed, which could affect human and animal food category, especially to the poorest nations that are in dire need of food. Also, only two countries (USA and China) are the major producer of corn, which could create the inflation in prices. This kind of situation could influence the major companies to move away from the PLA production (Kingsland, 2010).

To overcome this threat, there has been some practices to use agricultural by-products as a potential substrates for the production of PLA, which includes cassava starch, corn cubs, corn stalks, beet molasses, wheat bran, rye flour, sweet sorghum, sugarcane press mud, barley starch, corn fiber hydrolysates, lignocelluloses and hemicelluloses, cellulose, carrot processing waste, hydrolysates and potato starch. In the same way, kitchen wastes, fish meal wastes and paper sludge has also been successfully tested as a substrate for the PLA production.

Utilizing the carbohydrate sources from food and agricultural waste for the production cycle of PLA, corn consumption and direct land for the PLA production can be decreased by large extent and the criticisms and debate concerning the food source usage and land used for packaging materials can be resolved (Jamshidian, et al., 2010). On top of that, the possible positive outcome of the ongoing research and development process of PLA production using microorganisms to convert greenhouse gases directly into lactic acid will definitely help to solve the problem of corn dependency and land use.

13.4 Circular Economy

Ellen MacArthur Foundation (2015) describes circular economy as a restorative and regenerative system by design which aims to keep the materials at their highest utility and value at all times, distinguishing between technical and biological cycles. The resources are regenerated in the biological cycle and are restored or recovered in technical cycle. This smart and promising alternative has been successfully implemented by many product and businesses. In short, circular economy offers affirmative progress cycle that conserves and improves natural resources, optimize yields of the resources and reduces the threat managing the supply and flow of renewable resources. It encourages revealing and cutting out the harmful externalities that has effect on food, shelter, health, land use, air, water and other human utilities along with the actions to eliminate noise pollution, toxic emission, and climate change caused by the product life cycle (Ellen MacArthur Foundation , 2015).

On the contrary, the economic model of most of the products and businesses today take liner approach, to be exact ‘takes, make and dispose’ relaying on huge quantity of inexpensive, readily available non-renewable resources and energy. This model is extremely unsustainable and is at the peak of its existence as there are very limited non-renewable resources in the planet. Therefore, circular economy encourages the business to make their product reusable, recyclable, and from renewable resources and energy.

The bio-based biodegradable thermal pallet cover definitely justifies the circular economy concept for its lifecycle as it is manufactured using sustainable resources which are reusable, recyclable and compostable. The circular economy lifecycle of NATIVA film, which are manufactured using NatureWorks, Ingeo™ PLA resins is shown in Figure 24.

Figure 24. Circular economy of PLA products (Taghleef Industries Group   , n.d.)

In brief, plants require energy form the sun, CO_2 from air and waters and minerals from the soil for their growth using the photosynthesis process. During the photosynthesis process plants produce starch/sugar which is preserved in them. As discussed earlier the starch and sugar is then converted into lactic acid by the process of fermentation with the help of microorganisms and by the polymerization process the lactic acid is turned into PLA. Then it’s extruded and into bubble wrap and PLA film to make packing product.

Considering the short loop, the product can be reused for multiple times and after multiple reuses when it becomes useless it can be sent back to PLA recycling facilities to break down the product into PLA resin and we can continue the cycle.

For the long loop, the packaging product waste is sent to the composting facilities, where it is composted into biomass, water and CO_2 which was absorbed by the same plant in the first place. Eventually, the biomass, water and CO_2 go back to the environment and absorbed by the plants. In this way the cycle continues (Taghleef Industries Group , n.d.).

14 Financial Analysis of BBTPC

Since the manufacturing facility, process, wages, and other manufacturing expenses will be similar in both the products, only the financial activities which are dissimilar are compared to study the feasibility of the biodegradable thermal pallet cover. The company presently manufactures most of the products using backed aluminum foil as the outer reflective layer for their products and low density polyethylene (LDPE) resign for manufacturing the air bubbles. There has been some successful practise of using the metalized polyester (MetPET) film instead of backed aluminum, which significantly reduces the cost of manufacturing without compromising the performance of the product. The purposed biodegradable material will consist of metalized polylactic acid (MetPLA) film for the reflective layer and polylactic acid (PLA) resigns to manufacture air bubbles.

The configuration of the backed aluminum, MetPET and MetPLA are presented below:

- MetPET Cover: MetPET + LDPE+ LDPE bubble wrap
- Backed aluminum cover: aluminum foil + PET + HDPE +LDPE bubble wrap
- PLA Cover: vacuum coated aluminum layer + Core PLA + Sealable PLA + PLA bubble wrap

<u>Unit Price for presently materials</u>

Backed aluminum foil	0.314£/m^2
MetPET Film	0,083£/m^2
LDPE Resin	1.19£/kg
SilverSkin Tape	0.03£/m
Double Sided Tape	0.06£/m

<u>Unit price for biodegradable materials</u>

Metalized PLA	0.122£/m^2	
PLA resin	1.76£/kg	
Biodegradable tape	0.02£/m	(Alibaba, 2017)
Biodegradable double sided tape	0.08£/m	(Kingfisher Tapes, 2015)

To compare different materials we need to set up the functional units. Functional units for the financial comparison of the materials used in manufacturing three different kinds of pallet cover are given below:

Pallet cover size Euro, 1.2m x 0.8m x 0.9m (high)
Total surface area of a pallet 4.56 m^2 (both side = 9.12)
Production of 150 m^2 of bubble foil requires 11.50 kg of resin (Jadudova, et al., 2015)

Hence, production of 1 m^2 of bubble foil requires (11.50 / 150) = 0.077 kg of resin
Production of 1 pallet cover requires (4.56*0.077) =0.35 kg of resin
Resin per cover 0.35 kg
Tape per cover 4.90 m
Foil per cover (4.56*2) = 9.12 m^2 (includes both external and internal layer)

Table 4. Financial comparison table of different pallet covers

Materials	Unit Price (£)			Materials used per cover	Price/materials(£)		
	Backed Aluminum	BBT PC	MetPET		Backed Aluminum	BBTPC	MetPET
Resin (kg)	1.19	1.76	1.19	0.35	0.42	0.62	0.42
Foil (m^2)	0.31	0.12	0.08	9.12	2.86	1.11	0.76
Tape (m)	0.03	0.02	0.03	4.90	0.14	0.12	0.14
Double sided tape	0.06	0.08	0.06	4.90	0.28	0.42	0.28
Total materials price/cover					3.71	2.26	1.60

Note: All the calculations for the existing materials prices are based on TP3 Global internal price, estimations and various quotations received from different companies. The Length of the tape and area of the foil are measured during the manu-

facturing process. Calculation was done with the assumption of manufacturing the products in UK, therefore the products that are not available in UK are searched and planned to be imported from China with the delivery charge of 2£/kg, which is also included in the calculations. Therefore, there could be a fluctuation in the price of different material with the change of country in regards of delivery charges and exchange rates in that particular time and place.

Assuming the company sells 180000 covers per year, we can calculate the difference investment per covers:

<u>Backed aluminum cover</u>

Total material expenses per cover =	3.71£
Total material expenses in a year (180000 *3.17£) =	667647.49£

<u>MetPET cover</u>

Total material expenses per cover =	1.60 £
Total material expenses in a year (180000 *1.60£) =	288437.89£

<u>BBTPC cover</u>

Total material expenses per cover =	2.26£
Total material expenses in a year (180000 *2.26 £) =	407116.80£

Therefore, the expenses difference in manufacturing a BBTPC cover compared to a backed aluminum cover per year is calculated as follows:

=667647.49£ - 407116.80£

= 260530.69£

Conversely, the expenses difference of manufacturing a BBTPC cover compared to a MetPET cover per year are calculated as follows:

=288437.89£ - 407116.80£

= -118678.91£

To conclude, it is not only ecological but also economical to manufacture BBTPC in compare to widely used backed aluminum pallet cover. By shifting from backed aluminum pallet cover to BBTPC, a saving of 260530.69£/year can be made only with the wise material selection. On the other hand, MetPET pallet cover is still more economically preferable option to the BBTPC, with the estimated loss of 118678.91£/year using BBTPC over MetPET Pallet cover. However, with the rising oil prices and increasing pressure from the environmental policies, such as implementation of 'green taxes' and advantages of various environmental grants and support for the greener alternatives, it is still more reasonable to manufacture BBTPC over MetPET pallet cover.

15 SWOT Analysis of BBTPC

SWOT analysis is the procedure of identifying the strengths, weaknesses, opportunities and threats of an organization or a product. It is an analytical structure that investigates what can be or cannot be achieved with the subjected product or idea. The analysis of above mentioned areas to help understand the risks and increase the resources efficiency before the promotion or production of the product (Investopedia, 2017).

STRENGTHS	**WEAKNESSES**
• Renewable source for the production • No toxic fumes even during incineration • Less greenhouse emission compared to similar traditional products • Compostable in industrial facilities promoting circular economy and carbon recycling in the environment • Safer production because of the absence of potential explosion due to petroleum • Landfill reduction and prevents marine water plastic contamination • Low energy input, 65% or less energy is required for the production in compare to conventional products • Competitive and decreasing price with use of renewable resources and technological advances, in contrast to the ever-increasing petroleum product price because of their limited sources (Kushner, 2016)	• End of life infrastructures are limited • Careful sorting and proper labeling is essential • It will only degrade in industrial composting facilities and at there are only limited facilities present in the world

OPPOURTUNITIES	THREATS
• Can be implemented to various other application as well • Packaging waste reduction and proper management • Helps to meet EU 2030 packaging waste obligation creating a circular economy. • Reduce pressure and pollution emission to the environment	• Foreign contamination can raise the cost, reduce the process effectiveness and efficiency • Inadequate and not well-defined use of compost in many countries and wasting the compost instead of using it as agricultural fertilizer • Concern about the use of GMO crops • 'Fuel vs. Food' debate and Land use debate

16 Disadvantages of BBTPC

Even with various important benefits over traditional products, there are some disadvantages of bio-based biodegradable thermal pallet covers which are described below:

- Improper disposal of the product can lead to water and soil pollution and it might threat the wildlife and aquatic species. The product may end up in the landfill, which is the worst of all the options. We should always try to eliminate this option in any product's end life. They are stable in the landfills with no statistically significant amount of methane released, but in long life cycle it can cause biodegradation of landfill wastes, resulting methane emission to the atmosphere (Nature Works, 2017) (International Solid Waste Association, 2015).
- Clear labeling, proper disposal and recycling instruction is very essential for the product to prevent the product contamination to the similar counterparts, which would affect the recycling and environmental friendly disposal of the product.
- The biodegradable thermal pallet covers will only degrade in industrial composting facilities and at there are only limited facilities present in the world (Kushner, 2016).

- As in most of the products with renewable source of bio based raw materials, there is always growing argument over the land used to manufacture the product versus the land for growing food: the ‘fuel versus food’ debate. European Bio-plastic Association states that the land use to produce bio-plastics only amounts to 0.006% of the global agricultural area, so there is no competition between the re-newable source to produce bio-plastics and food production (International Solid Waste Association, 2015). There is also a growing concern about the use of ge-netically modified crops to produce PLA and other Biodegradable polymers as they are historically produced using GMOs, but there are many GMO-free produc-ers available today (Bradley, 2010).
- Even with the advantages of treating in all levels of waste management hierarchy, appropriate sorting, recycling, composting structures for the end of life options are still inadequate. There is a need of enhancement in the recovery rate of the PLA based products which can be achieved with the coordination and effort with the in-dustries, commodity groups, government bodies and other related authorities (Aguirre, et al., 2016).

17 Conclusion

Sustainability is more imperative than ever as we are approaching the crucial time for our environment. It is time we seriously consider greener alternatives not only for packaging industry but also for our current way of living. To address the problems raised by the envi-ronmentally irresponsible packaging waste, bio-based biodegradable product designed for maximum reusability and easy recyclability could be a perfect option. With the rising oil prices and increasing pressure from the environmental policies, such as implementation of ‘green taxes’ in most of the countries, biodegradable products will be the mandatory so-lution in the near future.

PLA was considered as the main raw material for the production of biodegradable thermal pallet cover mainly because of their popularity and market availability. Moreover, virtually the entire portion of the thermal pallet cover can be easily prepared using PLA, which also helps to define the product specification and does not decelerate or affect the degradation process, since the bubble wrap and metalized foil contains the same material. The product will also implement the circular economy concept for its lifecycle as it is manufactured using sustainable resources which are reusable, recyclable and compostable.

As per the set objective, the solution is bio-based and biodegradable, is readily available in the market, can be manufactured using the existing technology, equipment and process and is expected to compost in the industrial composting meeting the different standards requirements. Nearly all of the materials purposed in this project for the production of bio-based biodegradable thermal pallet cover are individually certified as bio-based and compostable, so we can claim that the final product also possesses similar properties. However, only final products are permitted to use the compostable certification. Therefore, the product has to undergo the compostability test following the officially recognized standards, and only after that it can be certified as a compostable product. It is recommended to perform proper performance analysis and biodegradation test to prove the accurate feasibility of the product before final production. Every idea should be critically analyzed for their downsides and full life cycle before proclaiming them as an ultimate solution.

The main problem considering proper end of life solution for the biodegradable products are identification, collection, and sorting. This will not be issue for the biodegradable thermal pallet covers, as costumer pools of this product are corporate business mainly large pharmaceutical companies, logistical companies, and perishable companies. These covers are used in large quantities in a certain route for logistical purpose only. The waste generated is usually a short loop waste, which means that it is generated in specific location in defined and short period of time. Towards the end of the journey, the covers can be easily sorted and collected right there in the location, for example, in the warehouse. It would be easy to collect and transport it back to the respective recycling and composting facilities without any complexities. Still there are limited end of life infrastructures for the biodegradable plastic products. With the growth in market of biodegradable plastic products, it is certain that there will be more of these facilities in future. Therefore, the proper end of life process like recycling, reusing, and composting will be more economical, effective, and efficient in the future.

Even though the bio-based biodegradable bubble foil was studied only as a raw material in the manufacturing of thermal pallet covers, it can be used for various other insulation purposes such as insulated thermal carry bags, as cardboard box liners and covers, as building insulation and as other various shapes and sizes of cargo carrier covers and internal cargo carrier liners. The use is not limited only to thermal pallet covers.

On the basis of the results of this thesis, it can be concluded that the bio-based biodegradable thermal pallet cover is a feasible and viable solution as a sustainable and environmentally and socially responsible alternative to currently manufactured thermal pallet covers.

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