EXTRUSION PROCESS AND CALENDERING

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Plastics can be shaped into a wide variety of products:

- Molded parts
- Extruded section
- Films
- Sheets
- Fibers for textiles

The main processes adopted in the PolyBioskin project will be illustrated. In this section the attention will be focused on extrusion and calendering processes.

To shape a thermoplastic polymer, it must be heated so that it softens to the consistency of a liquid (this form is called polymer melt).

Important properties of polymer melts are:

- Viscosity
- Viscoelasticity
The polymer viscosity is a fluid property that relates shear stress to shear rate during the flow.

Due to its high molecular weight, a polymer melt is a thick fluid with high viscosity.

Viscosity of polymer melt decreases with shear rate, thus the fluid becomes less viscous at higher shear rates (shear thinning behaviour).

Viscosity decreases with temperature, thus the fluid becomes more fluid at a higher temperatures.

Viscosity as a function of temperature for selected polymers at a shear rate of $10^3$ s$^{-1}$.
VISCOELASTICITY

- It is the property of a material that determines the strain it experiences when subjected to combination of stress and strain.

- It is possessed by both polymer solids and polymer melts.

To better understand viscoelasticity the concepts of elasticity and viscosity must be defined.

➢ **Elasticity** is the tendency of solid materials to return to their original shape after forces are applied on them. When the forces are removed, the object will return to its initial shape and size if the material is elastic.

➢ **Viscosity** is a measure of a fluid's resistance to flow. A fluid with large viscosity resists motion. A fluid with low viscosity flows. Since heating reduces viscosity, these materials don't flow easily.

➢ **Viscoelasticity** is the property of materials that exhibit both viscous and elastic characteristics when undergoing deformation. Synthetic polymers, wood, and human tissue, as well as metals at high temperature, display significant viscoelastic effects. In some applications, even a small viscoelastic response can be significant.

The difference between elastic materials and viscoelastic materials is that viscoelastic materials have a viscosity factor and the elastic ones don't. Because viscoelastic materials have the viscosity factor, they have a strain rate dependent on time. Purely elastic materials do not dissipate energy (heat) when a load is applied, then removed; however, a viscoelastic substance does.

Stress- Strain curves for purely elastic material (a) and a viscoelastic material (b). The coloured area is a hysteresis loop and show the amount of energy lost (as heat) in a loading and unloading cycle.
EXTRUSION DEFINITION

The extrusion technique is a continuous process in which a polymeric molten material is pushed through a die of the desired section. This process is generally applied to plastics and metals.

The plastic raw material is plasticated by means of a screw plastication unit. A schematization of a typical plastic extrusion process is reported below:
WHAT CAN BE DONE WITH AN EXTRUDER?

Here’s a scheme in which it is reported what can be done with an extruder.

The extrusion technique can be used for:

- Profile extrusion
- Blown film extrusion
- Calandering
- Fibre extrusion
- Pipe & tube extrusion
- Recycling of plastic materials (for example from packaging industries).

Extruder

- Compounding
- Master batch production
- Lab Extrusion
- In-line compounding

Compounding
- Compounding of technical thermoplastic
- Fillers incorporation
- Polymers reinforcing
- Flame-retardant compounds
- Cable compounds
- Foam applications

Lab Extrusion
- Custom colouring
- Colour matching
- Pigment concentration up to 80%
- Quality control

In-line compounding
- For scale-up to production processes
- Formulation development
- Quality control
- Injection moulding compounder

Lines for the production of sheets and films

Cold processing
- Long fibers reinforced thermoplastics lines

Formulation development
- Feasibility studies

Pigment concentration up to 80%

Injection moulding compounder

- Lines for the production of sheets and films

- Injection moulding compounder

- Quality control

- Foams

- Master batch production
- Lab Extrusion
- Extruder

Raw material

Pellets

Processing

End product

Injection molding

Profiles

Tubes
EXTRUDER CLASSIFICATION

EXTRUDER TYPES

- Single screw extruder
- Twin screw extruder
- Co-rotating
- Counter-rotating

The polymeric matrix and any required additives, are fed into the extruder via gravimetric solid feeders (and via a peristaltic pump in case of liquid additives) in a pre-established percentage.

Once in the screw, with the heat flow generated by the heaters placed along the barrel and the heat generated by the rotary movement of the screw (shear forces), the material is melted and mixed.
SINGLE SCREW EXTRUDER

- On a single screw extruder one screw rotates in the barrel. It is possible to obtain different geometries so it can be used in different applications. In particular, it is mostly used for processing thermoplastic into semi finished products.

- Pressure generation and material conveying are the most important functions of this kind of extruders. This, single screw extruders usually have an increasing diameter from the hoppers to the die, in order to generate greater pressure. Because of having only one screw, the mixing is very poor consequently they cannot be used for extrusion compounding.
TWIN SCREW EXTRUDER

- The twin screw extruder is the most frequently used extruder because it can be used in many kind of applications. Thanks to this extruder it is possible to: plastifying, mixing and homogenizing the polymeric molten material.

- In this kind of extruders the flow generated has a C shape, which has the properties of a positive pumping, decreasing the influence of material viscosity in its conveying and generating a very effective pumping.

- However there are some disadvantages that can be encountered. For example: screws are pushed against the barrel, which makes necessary to avoid high screw speeds; inefficient mixing do to fast material conveying.

This kind of extruders have two identical screws that rotate in parallel in the same direction. Screw configuration, barrels and feeders are designed depending on the kind of filler, fibre, polymer, percentages of each component…

These type of screws are used in long extruders, with a high L/D (length/diameter) ratio. Due to the low pressure with which these extruders work, the addition of liquid additives by peristaltic pumps is an easy process.

The flow dependence on material viscosity is higher than in counter-rotating screw but lower than single screw extruders.

In this kind of extruder screws the material goes alternatively from one screw to the other and thus mixture is more homogeneous than in counter-rotating screw extruders.

In this kind of extruders the flow generated has a C shape, which has the properties of a positive pumping, decreasing the influence of material viscosity in its conveying and generating a very effective pumping.

Some drawbacks of this process are:

- screws are pushed against the barrel, which makes necessary to avoid high screw speeds.
- Inefficient mixing. The faster the material is conveyed, the less efficient the mixing is.
EXTRUSION COMPOUNDING

In the extrusion compounding the extruder is used to simply mix or to add a filler or a reinforcement (like fibers) into the polymeric matrix. Also additives can be added with the purpose of modifying the material final properties (mechanical, physical, chemical or optical properties). For example, a modification is necessary in those case in which the material do not respond to specific requirements correlated to a specific final application.

There are some cases in which the improvement or modification of the material properties becomes necessary; for example, when the material is not easily processable (due to its melting temperature, viscosity, etc.).
In order to better understand the extrusion compounding process, in the figure below are reported the main components of a compounding extruder.

By extrusion compounding it is possible to obtain mixtures in different **percentages**. Depending on the quantities of the additives and/or filler to be added, it is possible to obtain:

- a blend, a compound or a master batch.

**Blend**

It is referred to a mixture in which at least two polymers are mixed together.

**Compound**

It is a mixture in which a specific percentage (in little quantity) of an additive, a filler or a reinforcement is incorporated into the polymeric matrix.

**Master Batch**

In this case the additive is added in high percentage (high concentration). The concentrate is successively diluted in a polymeric matrix.
COMPARISON BETWEEN CO-ROTATING AND COUNTER ROTATING

Counter-rotating

One screw turns clockwise and other counter clockwise.

Less self wiping.

More likelihood of material stagnation.

Less mixing than co-rotating.

Less shear compared to co-rotating and single screw extruder.

Less power consumption than single screw extruder.

Co-rotating

Both screws either turn clockwise or counter clockwise.

More complete self wiping.

Less likelihood of material stagnation.

Better mixing.

Total shear is more.

Less power consumption than single screw.
It is possible to list the characterization and the mode of operation of extruder screw elements.

**Pitch**
- It is a geometrical quantity and influences the chamber volume and residence time.

**Chamber volume**
- It describes the available volume in the screw flight.

**Self-cleaning**
- It becomes possible by the “Erdmenger profile” of the screws and is ideal for conveying elements.

**Residence time**
- The residence time of the material in the screw is determined by the pitch (the higher the pitch is, the shorter the residence time will be). However it is important to observe that the residence time in the extruder is determined by the screw speed and the length of the processing unit!

**Conveying effect**
- It describes the element’s ability to push the material forward. The more flights there are and the smaller the pitch is, the stronger the conveying effect will be.

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**The screw shaft allows transmission of high torques.**

The **pitch** of the screw is the distance between two consecutive flights. The screw flight pitch is directly related to the screw helix angle, which is the angle between the screw flight and the plane perpendicular to the screw axis.

**High performance elements** can lower the energy input into the product with very high distributive and dispersive mixing action.

**Kneading and mixing elements** allow the dispersion and distribution of loads and additives inside the polymer matrix. They are placed in the melting and mixing zones.

**Conveying elements** their mission is to make the material advance through the screw, for this reason, they are placed in the feeding, degasification and metering zones.
The representation of conveying elements and kneading elements in a screw configuration draw is easy. Conveying elements are represented as a diagonal line and kneading elements are represented like a stair.

In a co-rotating twin screw extruder it is possible to individuate six different zones:

1. Feeding zone
2. Melting zone
3. Secondary feeding zone
4. Mixing zone
5. Degasification section
6. Metering zone

**Feeding zone**

This section allows the pushing and material compressing eliminating the air retained between the pellets. In this zone the first screw elements must have a small pitch (to avoid the retreat of the material), then the other screw elements must have medium or high pitch in order to increase the conveying speed.

**Melting zone**

In this zone the melting of the material occurs. The melting process is influenced by the screw speed, the residence time and the screw geometry. The energy for melting is provide mainly by the shear forces generated by the screw rotation. In this part of the screw it is also suitable to generate a degasification area, in order to eliminate the gases generated during the material melting.

**Secondary feeding zone**

This is an optional zone. It is used when some additives are not correctly dragged due to the incomplete melting of the polymeric matrix. The material fed in this secondary zone can be properly dragged because the material is melted. Furthermore, this secondary feed is appropriate for those additives very susceptible to be degrade at high temperatures and long residence times.

**Mixing zone**

Here the material is mixed and homogenized. It is possible to distinguish two kinds of mixing: dispersive and distributive mixing. The dispersive mixing breaks the agglomerates and reduces the particle sizes. The distributive mixing allows the homogenization of solid and liquid particles inside the melted matrix.

**Metering zone**

It is the last section, its mission to provide pressure to the melted material to make it go through the die. Usually the last element pose a lower pitch in order to provide a higher pressure to make the material go through the die.
PROCESSING UNIT: HEATING ELEMENTS

Induction heaters
- The barrel is heated from the resistance offered to the eddy current set up by the flux.
- Advantages: accurate control of temperature; good provision for cooling the barrel; no possibility for hot or cool spots.
- Disadvantages: relatively high cost.

Steam heating
- The high specific heat and latent heat of vaporization of water makes steam an excellent heat transfer medium. However, this system is not frequently used because of low maximum temperature that can be achieved, a need of working with high pressure piping, frequent leaks of steam that require shutting down of heating for repairs, and corrosion effects.

Cast-in heaters
- The insulated heating elements are cast into semi-circular or flat aluminium blocks which are machined to match the surface to be heated.

Fluid heating system
- The heating fluid, that is the most commonly used for extruders is oil. It may be heated by any suitable means (mainly electrical). The heating system consist of a heater, a circulating pump, a surge tank and a heat transfer channel in the extruder barrel.

Band heaters
- They consist of Ni-chrome or other resistance wires mica or ceramic insulated, then encased in steel cover.

Schematic representation of a section of an induction heater.
Barrel cooling
- Barrel cooling is needed to prevent overheating that may cause degradation.
- For small extruders fans that blow air over or around the barrel are used.
- Other cooling systems used include: Cooling channels inside the barrel wall; Fins on the barrel or on heaters to speedup heat transfer; a water-fog spry over barrel; continuous controlled vaporization of liquid (water) and copper tubing carrying cold water (sometimes used).

Hopper cooling
- Water-cooling is used to cool the hopper throat to prevent bridging and to protect the rubber parts present in the screw support assembly.

Screw cooling
- Screw cooling may be recommended to prevent decomposition of heat sensitive materials.
- It should be carried out using the cooling fluid at the temperature above the softening point of the principal polymeric component.
PROCESSING UNITS: FEEDING ELEMENTS

Feeding means adding or discharging a certain quantity of material to or measuring process (in case of continuous mixing) throughout a defined time frame. The feeder typology must be chosen according to the type of material (pellets, powders or fibers) in fact, they can influence the dosing ability and accuracy.

Feeding problems are mainly related to additives dosage. Additives must be added in the correct percentage. Even though additive hoppers and pump for liquids are calibrated, additives dosage could not be the adequate, being higher or lower than it is programmed. An incorrect additive dosage can be related to many factors. Between the main causes, inappropriate mass flow and additive nature are the most important. Additives dosage with hoppers is sometimes a little bit difficult due to their nature, additives can be in fibre, pellets or powder form. Hopper screw shape should be changed depending on the kind of additive.
A screw feeder for handling difficult material can require a special feed screw design and can be configured in numerous ways to ensure that the feed screw is continuously filled with material of a consistent bulk density. For instance, the feeder can have one feed screw with no agitator (Figure a), one or two screws with a vibrated trough or a pulsing flexible-wall hopper, one screw with a concentric agitator that operates at the same or a different speed (Figure b), or one screw with one or two agitators mounted above it (Figure c).
• In case of fibres, they tend to pile up and a metal screw makes them stay between its spirals, which makes the fibre advance only when there is quantity enough in the screw. This makes the addition of the fibre not continuous. In this case the use of a plastic screw without holes in the middle could solve the fibre addition problem.

• On the other hand, powder materials are better dragged via a metal screw due to the holes in the screw spirals. For additives in pellet form it do not matter what kind of screw is used, pellets are usually correctly dragged with both screw typologies.

• Product Bridging or “arching” and rat-holing are both issues that result in a no-flow condition. Bridging, is a case where material that is being discharged or fed forms a bridge or arch over the feed auger or discharge point in a silo cone/hopper. Rat-holing is a condition where the material forms a hole or narrow channel above the feed auger or outlet in a hopper while the remaining material is stationary against the hopper wall. Both of these conditions result in the product not flowing as desired.

• There are various ways to combat these product flow issues; hopper design, vibration, conditioning screws, and fluidizing nozzles. This is where knowing the material flow characteristics pays off in the design and use of the equipment. Conical and angled hoppers both create a distinct flow path for the material, it is up to the design engineer to calculate the correct pitch of the hopper walls that best fits the products flow characteristics. Proper hopper design is key but not always the solution. Vibration is commonly used when handling chemicals and other bulk solids materials. When a screw feeder is designed into your process often times a second conditioning screw is utilized to help keep a consistent material flow source to the auger. On the discharge cone of a silo system for example; vibration, air fluidizing nozzles, and bin activators are all ways to help condition product flow and prevent bridging and rat-holing issues.
The role of a die is to form the melt into a desired linear product: fibres, films, sheets, profiles, rods, etc. The die is a channel, whose profile changes from that of the extruder bore to an orifice, which produces the required form.

The dies can be classified using different criteria. Considering cross section of the extrudate one may recognize dies to produce:

- Solid Cross-Sections
- Hollow Cross –Sections

Another classifications scheme is based on the die attachment to the extruder barrel:

- Straight –through dies
- Cross –heat dies
- Offset dies

A Typical Die Design for extruding a solid rod is reported in figure.

- In the figure, $D_d$ is the diameter of die orifice, $D_b$ is the diameter of bore of extruder barrel, $\alpha$ is the lead-in angle, and $P$ is the die land.
- Because of the screen pack and breaker plate assembly, the pressure in the extruder ($P_E$) is reduced by the pressure loss across the assembly ($P_L$).
- Since the die outlet is at atmospheric pressure, the working pressure is the die pressure ($P_D$) given by the difference: $P_D = P_E - P_L$. 
• As screw rotates inside barrel, polymer melt is forced to move forward toward die (like in an Archimedean screw).

• Principal transport mechanism is drag flow, \( Q_d \), resulting from friction between the viscous liquid and the rotating screw.

• Compressing the polymer melt through the die creates a back pressure that reduces drag flow transport (called back pressure flow, \( Q_b \)).

• Resulting flow in the extruder is: \( Q_x = Q_d - Q_b \).

The shape of the die orifice determines the cross-sectional shape of the extrudate. Common die profiles and corresponding extruded shapes are summarized in figure.
According to their manufacturing, the polymers are obtain as a melt or powder. In this condition they are difficult to process further. By pelletizing, particles (pellets) of the same size and shape are produced, which facilitates the further processing of the polymer. During the pelletizing, the polymer properties are “frozen”; in addition the shape size and weight are fixed.

- Pelletizing problems are mainly related to the speed selection. Pelletizer speed must be selected depending on the extrusion speed. If pelletizing speed is not correctly selected plastic filaments can be broken, if speed is too high, or material is accumulated in the melted filament, if speed is too low.

- However, pelletizer has a minimum speed and if extrusion speed is too low, maybe the minimum pelletizing speed still being too high. If this happens, plastic filaments must be manually collected to be then manually introduced into the pelletizer.

- In some cases pellets are not well cut. This can happen because of a humidity excess in the plastic filament or due to some pellet which can be clogging the pelletizer.
FLAT FILM EXTRUSION

- Generally three main equipment can be identified in flat film extrusion process. They are for cooling, taking off and winding up.

- In flat film or sheet production the first objective is to spread a continuous polymer melt stream coming from an extruder into a die (flat die), which terminates in a rectangular and wide cross-section, having a small gap.

- After the die the molten extrudate is cooled on calender system and solidifies.

- Products of less than 0.25 mm in thickness are referred to as films and those over 0.25 mm are referred to as sheets.
The molten polymer stream coming from an extruder must be distributed as uniformly as possible into a rectangular shaping area so that a thin wide sheet or film of uniform thickness is produced continuously. Between the melt pipe, coming from the extruder, and the rectangular die lips (flat die) a distribution channel (usually called a manifold) is needed.

The most common dies utilise either the simple ‘T-slot’ or the ‘coat hanger’ geometry.

- T-slot dies are the simplest to manufacture. They have a large manifold of usually circular cross-section, which is constant across the entire width of the die. There is very little resistance to flow from the centre (feed) to the side ends of the die and even flow distribution is accomplished by the flow controlling action of the die lips.

- In the coat hanger geometry, dies usually involve a manifold, a preland, possibly a flow restrictor (also called a ‘choker bar’), a secondary manifold and finally the primary land (die lips).

- Such dies are used for low viscosity polymers (high melt flow index resins) mainly for extrusion coating applications. A less common type of die is the ‘fishtail’ design.
CALENDERING

The calender is able to process the polymer melt into a sheet or film. When first developed it was mainly used for processing rubber, but nowadays it is commonly used for producing thermoplastic sheets, coatings and films. In fact, the best polymer for calendering are thermoplastics due to the fact that they soften at a temperature much lower than their melting temperature, giving a wide range of working temperatures.

The polymer blend (1) is heated and fed between two rotating main calenders (2). The pulp is pressed to a rough thickness (3) and is then rolled by subsequently rollers to the desired thickness. The thickness of the polymer sheet is dependent mainly on the gap between the last two rollers.

The rate at which the extrudate is cooled determines several important properties of the finished product. Longer cooling means there is more time available for crystal growth and thus the crystallites will be larger. Crystallinity affects the density, optical properties, coefficient of friction, impact, barrier and other properties.
• The last set of rollers also dictate the surface finish, glossiness and texture of the surface.

• Polymer is ready for going through the rollers tends to follow the faster moving roller of the two that it is in contact with end it also sticks more to the hotter rolls.

• Calender typically end with a smaller roller at higher speed to peel the sheet off.

• The middle roller is kept cooler so that the sheet won’t stick to the other rollers nor will it split by sticking to both rollers which can happen.
There are 3 main types of calendering system:

- **I type**: This system it was for many years the standard calender used. It can also be built with one more roller in the stack.

- **Z type**: 

- **L type**: This design was not ideal though because at each nip there is an outward force that pushes the rollers away from the nip.
**L type**

- The L type calender are often used for processing rigid vinyl's and inverted L type calender are normally used for flexible vinyls.

- These both setups have become popular and because some rollers are at 90° to others their roll separating forces have less effect on subsequent rollers.

**Z type**

- The Z type calender places each pair of rollers at right angles to the next pair in the chain. This means that the roll separating forces that are on each roller individually will not effect any other rollers.

- Another feature of the Z type calender is that is that they lose less heat in the sheet because the sheet travels only a quarter of the roller circumference to get between rollers.
Advantages

• The calender is very good at handling polymer that are heat sensitive as it causes very little thermal degradation.
• It is good at mixing polymers that contain high amount of solid additives that don’t get blended or fluxed very well.
• It is possible to control the crystallization monitoring the extrudate rates.
• It is used for large amount production

Disadvantages

• It is a very expansive process to perform.
• If the thickness is below 0.15 mm then there is tendency for pinholes and voids to appear in the sheets.
• If the thickness is greater than about 1.52 mm then there is a risk of air entrapment in the sheet.
• The achievement of the desired thickness is a very difficult process. A highly qualified personal is required
FOCUS ON BIOPLASTICS EXTRUSION AND CALENDERING

During extrusion, final material problems are mainly related to its degradation and bad homogenization.

- **Degradation** of bioplastics can take place due to different causes. The main causes are a bad selection of the processing temperatures and a bad selection of screw speed. On the other hand, apart from bioplastics, additives can also suffer degradation due to its nature.

- **Poor homogenization** takes place due to a bad dispersion and distribution of additives in the polymeric matrix, mainly because of a lack of affinity between the plastic and the additive.

Humidity is a problem related to bioplastics when processed. In fact such biopolymers are sensitive to hydrolysis and degradation in presence of water during the extrusion process (like poly(lactic) acid (PLA) and polyhydroxyalkanoates (PHAs)).

Bioplastics processing window is very narrow and a wrong selection of processing temperatures can lead to plastic degradation. When bioplastic degradation occurs it becomes completely liquid and a color changing occurs. When a polymer degradation happens, the temperature profile along the extruder screws must be decreased until the final material is not degraded.
• Bioplastics degradation can also be related to shear stress. The higher the screw speed, the higher the material degradation, despite temperature profile along the screw is correctly selected.

• It is important to observe that also in the case in which the temperature profile is correctly selected, shear stress provides also temperature to the material and thus material has to withstand higher temperatures than expected.

• If temperature is correctly selected but material still liquid, two solutions can be applied:

  Reduce screw speed maintaining the same temperature profile.

  Reduce temperature maintaining the speed.

Each bioplastic must be processed at the correct temperature. These temperatures must be selected also depending on the kind of additive and the section of the screw in which it is added.
In the following table there are some temperature profile (on a semi-industrial COMAC EBC 25HT) of some biopolymers blends.

<table>
<thead>
<tr>
<th>Polymer matrix</th>
<th>Additive</th>
<th>T1 (°C)</th>
<th>T2 (°C)</th>
<th>T3 (°C)</th>
<th>T4 (°C)</th>
<th>T5 (°C)</th>
<th>T6 (°C)</th>
<th>T7 (°C)</th>
<th>T8 (°C)</th>
<th>T9 (°C)</th>
<th>T10 (°C)</th>
<th>T11 (°C)</th>
<th>Die zone (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLA2003D (NatureWorks)</td>
<td>Calcium Carbonate (OMYA)</td>
<td>150</td>
<td>175</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td>185</td>
<td>185</td>
<td>185</td>
<td>190</td>
<td>190</td>
<td>190</td>
<td></td>
</tr>
<tr>
<td>PLA2003D (NatureWorks)</td>
<td>PBAT C1200 (BASF)</td>
<td>150</td>
<td>175</td>
<td>180</td>
<td>180</td>
<td>180</td>
<td>185</td>
<td>185</td>
<td>185</td>
<td>190</td>
<td>185</td>
<td>180</td>
<td></td>
</tr>
<tr>
<td>PBSA FZ71PM (Mitsubishi)</td>
<td>Wood fibers</td>
<td>150</td>
<td>165</td>
<td>170</td>
<td>175</td>
<td>170</td>
<td>165</td>
<td>160</td>
<td>155</td>
<td>155</td>
<td>160</td>
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<td>165</td>
</tr>
<tr>
<td>PHB-V PHI002 (Naturplast)</td>
<td>Calcium Carbonate (OMYA) + ATBC (plast.)</td>
<td>170</td>
<td>175</td>
<td>180</td>
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<tr>
<td>Cellulose Acetate 1GTA30 (GIBAPLAST)</td>
<td>no</td>
<td>175</td>
<td>180</td>
<td>195</td>
<td>195</td>
<td>205</td>
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</table>

**PLA processing temperatures**: PLA processing temperatures range from 170 to 200 °C. If such additives are fed to the screw in a secondary feeding section temperature can be increased because remaining time of the additive inside the screw at high temperatures is almost a half of the time that the additive is inside the screw when it is fed from the beginning.

**PHAs processing temperatures**: There is a broad diversity of PHAs produced from different monomers which come from different feedstocks. PHAs thermal properties therefore depend on the kind of monomer. The content of each monomer in the final PHA affects to its melting temperature. Melting temperatures of PHAs range from 89 °C to 174 °C, although for every kind of PHA the processing window is narrower.
• Biodegradable polymers have also risen the interest to produce films and sheets, in applications like packaging and skin contact items, often used in sanitary and personal care products.

• Poly(lactic acid) (PLA) is the most used renewable and biodegradable polymer, due to its high tensile strength, good heat stability during processing, excellent biocompatibility and excellent gloss and transparency.

• Plastic films are highly used in products to be in contact with human bodies, such as food packaging, personal care and sanitary products. During the Polybioskin project a flat die extrusion through an AMUT unit, operating through a linear die of an adjustable thickness (between 3.0 mm and 1.4 mm), was used to produce biopolymeric PLA sheets and films with thicknesses ranging from 50 microns to 1 mm.

• The geometry used for the flat die distribution channel in the extruder head is the coat-hanger die, equipped with a straight distributor that ensures better homogeneity in the flow. The flow control rods must be provided with gaskets to prevent the escaping of melt polymer. The material that comes out from the die in the form of a molten plate goes immediately in contact with a system of thermostatic rollers to allow cooling and solidification.

• To obtain flexible PLA-based blends, maximizing the biobased content of the material, the addition of suitable biobased plasticizers was fundamental. The use of chain extenders is crucial for modulating the rheological properties increasing melt viscosity. Furthermore, additives with antimicrobial properties (like chitin nanofibrils) are usually added to these film formulations.

• Market formulations of these films are often very complex, as they contain fillers, such as calcium carbonate and talc, or nucleating agents, to control the crystallization of PLA during processing by increasing resistance without compromising the transparency.