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Strategies to improve sustainability in molded products

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Abstract

The purpose of this research is to improve the sustainability of a packaging by optimizing its design by means of a combination of strategies including the usage of environmental friendly raw materials, reduction of the amount of raw material required and optimization of moulding process. A methodology based on moulding process simulation with CADMOULD® v16 will be applied. Results show that biobased materials require higher thickness design due to their higher viscosity, although lower thickness can be used with recycled PP. Manufacturing by low pressure processes such as injection compression moulding instead of conventional injection moulding also leads to thickness reduction. A new parameter related to sustainable design, "weigh per packaged item", has been defined, which allows to evaluate different geometries for the product from a point of view of sustainable efficiency. Novelty of the research lies on the evaluation of the environmental advantage of biobased materials related to their processability and the definition of a new parameter to measure sustainability advantage related to design efficiency.

Keywords: Sustainable design; Bio-based material; Injection moulding; Design optimization.

1. Introduction

Nowadays, the world is increasingly more conscious of the importance of sustainability. Therefore, seeking for an alternative for plastic materials has become a high priority.

Redesign of products and processes in order to minimize environmental impact has arisen as an effective way of dealing with this crisis. In the specific case of plastic packaging, redesign implies investigating more sustainable alternative materials such as biodegradable or compostable materials, that can decompose by themselves at their end of life.

As well as the change of materials, redesign entails optimization of packaging focused on reducing resources consumption, minimizing waste and easing reuse and recycling. Redesign offers an integral and holistic strategy by considering all the aspects involved in the product cycle of life, from the very early stages of design to their final disposal, allowing to progress towards a more sustainable productive and consumption model that preserves the environment and that promotes human wellness in the long term.

A proper attitude to explore innovative ideas and creative perspectives can generate significant beneficious leading to achieve improvements in different fields such as environment, more efficient designs or even the chance to use new manufacturing processes with economic and environmental advantages regarding to the current processes.

The main goal of this research is to obtain a packaging redesign based on sustainability, including changes in geometry, material and process and keeping functionality. The research is focused in new geometries with more environment-friendly materials and contributing to a more sustainable future for the industry by optimizing the manufacturing process.

2. State of the art

Environmental problems are rising every day due to the current volume of production and usage of raw materials (Albanna, 2011). In a global world, where raw materials are far away from production facilities, packaging takes an increasing importance, being very contaminant elements and generating a huge amount of waste, mainly polymer waste (Dolge et al., 2021). That is the reason why design of products in general, and packaging in particular, specially those made of plastic, must be addressed from an environmentally friendly perspective and following the principles of circular economy. In 2020, the European Union launched an action plan focused on promoting circular economy in which different applications of biopolymers, packaging among them, were evaluated. Some solutions proposed by this plan were the reduction of plastic in packaging, design for reusing and the development of biopolymer applications. (European Parliament, 2020).

Biopolymers can refer to biobased origin of materials or to their biodegradability (Geueke, 2014). Biobased materials come from biomass, or renewable resources such as plants, microorganisms or seaweed (Coppola et al., 2021). Biocompostable materials can be biodegraded under composting controlled conditions giving as a result water, CO_2 and compost free from visible and toxic waste. Biodegradation process must not take more than 180 days, along which at least 90% of the initial mass must have been transformed into CO_2 and organic material. Biodegradable materials are decomposed by microorganism action to produce water, CO_2 and biomass under proper environmental conditions (Samalens et al., 2022).

On the other hand, injection moulding is one of the most extended polymer manufacturing processes. During the last few years, different researches have been conducted to evaluate the viability of the process with biobased materials (Körber et al., 2022; Alliota et al, 2022), but most of these are focused only on materials evaluation rather than on product design and development. In the same way, few researches are found studying the behavior of PLA with low pressure injection compression moulding (Lin and Lin, 2023) and hardly any reference is found related to biopolymers applications by injection compression moulding. An optimization methodology based on economic, ecological and technical criteria for an injection moulding food package is presented in Fernández et. al (2012).

The current research aims to carry out a methodological process to address an integral redesign of a packaging product including material, geometrical and manufacturing process alternatives. This integral approach is not found in the recent literature.

3. Materials and Methods

The research is based on a study case consisting on a chocolates packaging manufactured by conventional injection moulding. Figure 1 shows the CAD model used for CAE analysis and its general dimensions.

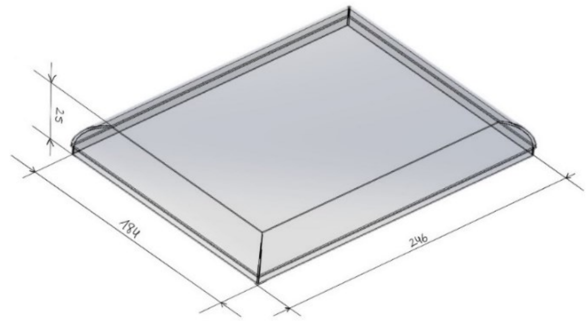


Figure 1. CAD model and dimensions for the cover chocolates packaging used for study cases

3.1. Materials

Current material used for the packaging is polystyrene Styrolution PS 165 N/L which is not the best choice from an environmental point of view. Alternative solutions for redesign purposes are biobased, biodegradable or biocompostable materials. Table 1 shows alternative materials evaluated for the redesign process.

Table 1. Evaluated materials with their bio-features and flow index value

Material	Bio-feature	Flow Index [cm³/10 min]
STYROLUTION PS 165 N/L	No bio-featured	3,4
INGEO BIOPOLYMER 3052D	PLA Biobased/biocompostable	12,87
INGEO BIOPOLYMER 3251D	PLA Biobased/biocompostable	73,33
INGEO BIOPOLYMER 6202D	PLA Biobased/biocompostable	12
MIREL P1004	PHB Biobased/biodegradable	-
PURELL EP 274P	PP Recycled countertype	20
PRO-FAX ULTRA SC973	PP Recycled countertype	143
BIONOLLE 1020MD	PBS Biocompostable	23,69

3.2. Methodology

A methodology involving redesign of geometry, material and manufacturing process is proposed in order to achieve a more sustainable packaging. Figure 2 shows the flowchart of the methodology followed.

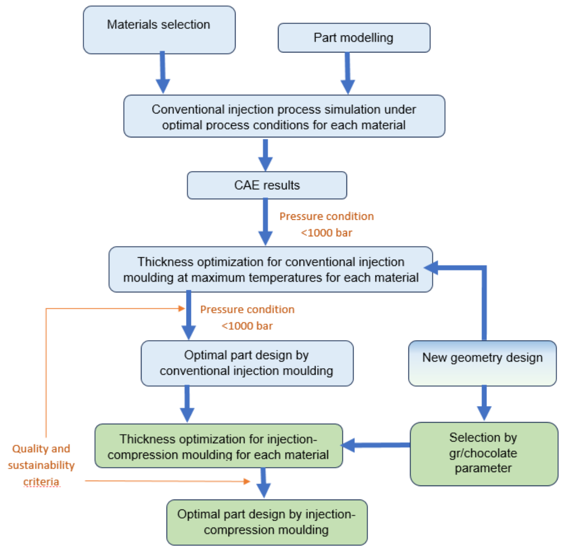


Figure 2. Flowchart of the methodology followed

At a first stage, simulations for conventional injection moulding are run for the base geometry with all the alternative materials at the recommended standard process conditions. After an iterative process, an optimization of the geometrical design by means of reducing thickness is achieved at these standard process conditions for each alternative material, taking as criteria a required injection pressure lower than 1000 bar.

At a second stage, a new iterative process is carried out for conventional injection model process under maximum temperature conditions to achieve a new optimized geometrical with a lower thickness design under the same criteria of requiring an injection pressure lower than 1000 bar.

At this point the optimized injection moulding conditions for each material are set, and, at a third stage, different geometrical proposals are considered for study.

Each of these proposals is evaluated by a new parameter, defined as gram of packaging material per chocolate unit. Let g be the total mass of the packaging in grams, and ch the number of chocolates that each packaging design is capable of lodging and let g/ch denote the parameter referring to sustainable quality of each design. This parameter allows a quantitative evaluation of sustainability for each redesign and will ease to make an informed decision on the better packaging design. This parameter allows to evaluate how efficiently the material of the packaging is distributed according to the number of chocolates that each packaging includes.

Once, the proposal with the best value of the parameter g/ch is chosen, a fourth stage is carried out to optimize thickness at both conventional injection moulding and compression-injection moulding. Since compression-injection moulding is a low pressure injection moulding process, it will allow to reduce the packaging thickness without overcoming the 1000 bar limit.

3.3. Simulation

CAE analysis has been carried out with CADMOULD v16, a CAE software tool used to simulate injection moulding processes. This tool is used to analyse different part and mould designs from the point of view of material, process conditions and geometrical aspects.

This software requires a CAD geometrical model, that in the proposed study case comes from SolidWorks. To emphasise the effect of the redesign variables, a simple feed system for the mould is used with a single injection point at the centre of the model, to keep the flow path as short as possible contributing to reduce maximum injection pressure required. Material data is introduced from the CADMOULD interface from a materials database, and process conditions are settled manually. Each material will use a different process conditions accordingly to the material characteristics shown on table 1.

4. Results and Discussion

4.1. Redesign for conventional injection moulding under standard process conditions

Table 2 shows results of redesigned thickness for the packaging model for each preselected material under standard process conditions recommended by CADMOULD. Simulation parameters for filling stage of the cavity are injection time, and injection and mould temperature. Results of maximum injection pressure and clamping force are registered.

Table 2. Simulation input data and results for redesign by conventional injection moulding at standard process conditions

Material	Geometry parameter	Simulation input process conditions parameters			Simulation results	
Material	Thickness [mm]	Injection time [s]	Injection temperature [ºC]	Mould temperature[ºC]	Maximum injection pressure [bar]	Clamping force [KN]
STYROLUTION PS 165 N/L	nom	1,3	230	40	401	1320
	-0,2	1,2	230	40	514	1369

	-0,4	1,1	230	40	689	1745
	-0,5	1	230	40	802	2066
	-0,6	0,9	230	40	905	2256
	-0,7	0,9	230	40	1272	3494
INGEO 3052D	nom	1,5	220	40	836	2404
	-0,1	1,4	220	40	951	2426
	-0,2	1,4	220	40	1083	2710
INGEO 3251D	nom	1.2	220	40	496	2140
	-0,2	1,2	220	40	692	1748
	-0,4	1,1	220	40	994	2348
	-0,5	1	220	40	1195	2837
INGEO 6202D	nom	1,5	220	40	818	2387
	-0,1	1,4	220	40	935	2257
	-0,2	1,4	220	40	1075	2647
MIREL P1004	nom	1,2	180	40	799	2330
	-0,1	1,2	180	40	912	2253
	-0,2	1,2	180	40	1002	2415
PURELL EP 274P	nom	1,3	215	35	408	1488
	-0,2	1,2	215	35	534	1377
	-0,4	1,1	215	35	724	1787
	-0,5	1	215	35	856	2106
	-0,6	0,9	215	35	1037	2466
PRO-FAX ULTRA SC973	nom	1,2	202,5	35	187	1687
	-0,2	1,1	202,5	35	257	714
	-0,4	1,1	202,5	35	367	952
	-0,6	0,9	202,5	35	567	1360
	-0,8	0,8	202,5	35	966	2509
	-0,9	0,7	202,5	35	1341	3516
BIONOLLE 1020MD	nom	1,3	215	40	437	1153
	-0,2	1,2	215	40	593	1666
	-0,4	1,1	215	40	824	2136
	-0,5	1	215	40	998	25134
	-0,6	0,9	215	40	1233	2902

Table 2 offers the values of redesigned thickness for each material ranging from nominal thickness (nom) to the minimum thickness satisfying the criteria condition of injection pressure lower than 1000 bar. This criteria condition has been chosen because it is a general value from which material could be degraded, although technologically higher pressures are allowed. It can be observed that Styrolution PS 165 N/L (original material) and Pro-Fax Ultra SC973 are the materials whose thickness can be highly reduced. Among the biopolymers the best behaviour is achieved with INGEO 3251D.

4.2. Redesign for conventional injection moulding under maximum temperature conditions

A new set of simulations is carried out varying packaging thickness from the nominal thickness value (1,4 mm) but considering maximum allowed material and mould temperatures according to suppliers' datasheets introduced in materials database. Figure 3 shows the thickness and pressures for each material applying the maximum criteria of 1000 bar.

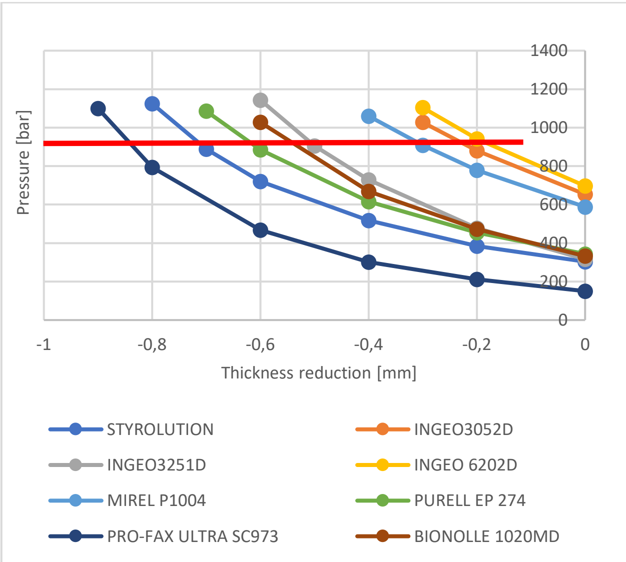


Figure 3. Redesigned thickness values for alternative materials at maximum temperature process conditions.

As expected, lower pressures are required when working with higher temperatures, and the thickness has been reduced in 0,1-0,2 mm for most of materials except for Pro-Fax Ultra SC973, whose result was quite exceptional also at standard temperatures and Bionolle 1020MD that has kept its thickness reduction at 0,6 mm regarding nominal value.

Table 3 shows simulation results for all materials at the optimum thickness at 1000 bar. As well as maximum injection pressure and clamping force, two new results are now considered. A result related to proper functionality of the part is distortion, that refers to deformations suffered by part after moulding due to residual stresses generated by differential cooling or overpacking. Distortion measures qualitatively and quantitatively how much real dimensions are deviated from design dimensions. Another result related to sustainability is the previously defined in section 3.2, g/ch. It allows to quantify the amount of material used for the total number of chocolates packaged. The lower this parameter is, the less material is required for each commercialized chocolate, and the better solution from a sustainable point of view is.

Table 3. Simulation input data and results for redesign by conventional injection moulding at maximum temperature process conditions

Material	Geometry parameter	Simulation input process conditions parameters			Simulation results				Sustainability parameter
Material	Thickness [mm]	Injection time [s]	Injection temperature [ºC]	Mould temperature [ºC]	Injection pressure [bar]	Clamping force [KN]	mass [g]	Maximum distortion [mm]	g/ch
STYROLU-TION PS 165 N/L	0,65	0,8	260	60	997	2617	39,9	0,66	1,7
INGEO 3052D	1,12	1,4	240	50	997	2538	79,1	2,83	3,3
INGEO 3251D	0,86	1	240	50	998	2384	62	1,13	2,6
INGEO 6202D	1,17	1,4	230	50	986	2497	83,1	2,23	3,5
MIREL P1004	1,04	1,1	190	50	991	2403	75,2	1,28	3,1
PURELL EP 274P	0,74	0,9	230	50	998	2394	37,4	1,76	1,6
PRO-FAX ULTRA SC973	0,53	0,8	215	49	987	2568	28	1,48	1,2
BIONOLLE 1020MD	0,81	0,9	240	50	1002	2397	56	10,78	2,3

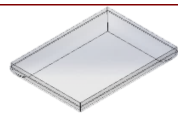
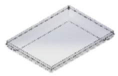
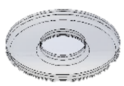
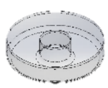
By analysing distortion data from Table 3, most of materials present adequate values, excepting Bionolle 1020MD whose distortion is too high due to its low Young Modulus. Ingeo 3052D y el Ingeo 6202D present values of 2,83 and 2,23, higher than the rest of alternative materials.

Taking into account sustainability parameter, Ingeo 3251D seems to be a good candidate because thickness can be reduced down to 0,86 mm, keeping functionality of the part with a distortion value of 1,13mm, and a value for the sustainability parameter of 2,6 g/ch. Another good candidate could be Pro-Fax Ultra, because it is the material with the highest reduction of material, 1,2 g/ch thanks to its high level of fluidity, and although distortion is a bit higher than for Ingeo 3251D, it can be considered a proper value to make sure packaging functionality.

4.3. Geometrical redesign

Different geometrical proposals have been analyzed from the point of view of sustainability, by evaluating the parameter g/ch. Table 4 shows the features of the geometrical proposals and the results obtained.

Table 4. Geometrical redesign proposals

Geometry	Model	Weight [g]	Main Dimensions [mm]	Number of chocolates	g/ch
Original		87,27	246x184	24	3,65
Small Original		55,39	193x139	15	3,69
Circular		108	Ø 271	31	3,51
Small Circular		73	Ø 216	19	3,83
Large Circular		131	Ø 302	37	3,54
Ring		102	Ø 261	24	4,25
Double ring		115	Ø 222	32	3,69

According to Table 4, circular and large circular geometries exhibit the lower values for the sustainable parameter g/ch, 3,51 and 3,54 respectively. Therefore, an alternative circular geometry is selected to continue with the redesign process. This kind of revolution geometry is also very adequate to implement a more sustainable manufacturing process which a lower demand of pressure such as injection-compression moulding.

4.4. Redesign for injection-compression moulding

The redesign process is completed by evaluating alternative manufacturing processes such as injection-compression. This process requires a lower injection pressure since injection is carried out with the mould opened and final distribution of the polymer into the mould is achieved by closing the mould. Therefore, pre-opening mould distance is a key input parameter for this process as well as injection time and temperature, and mould temperature.

Table 5 show analysis results for circular geometry applying injection-compression moulding.

Table 5. Simulation input data and results for redesign by injection-compression moulding at maximum temperature process conditions

Material	Geometry parameter	Simulation input process conditions parameters			Simulation results				Sustainability parameter
Material	Thickness [mm]	Injection temperature [ºC]	Mould temperature [ºC]	Pre-open mould [mm]	Maximum injection pressure [bar]	Clamping force [KN]	mass [g]	Maximum distortion [mm]	g/ch
STYROLUTION PS 165 N/L	0,66	260	60	7	853	3081	48,2	0,5	1,55
INGEO 3052D	1,1	240	50	5	813	2158	93	1,7	3

INGEO 3251D	0,8	240	50	6	999	2384	68,2	0,5	2,2
INGEO 6202D	1,16	230	50	5	886	2516	96,9	2,7	3,12
MIREL P1004	1	190	50	5	891	2458	84,8	5,3	2,74
PURELL EP 274P	0,71	230	50	5	1080	3503	42,8	2,74	1,38
PRO-FAX ULTRA SC973	0,5	215	49	5	1113	3258	34,6	1,7	1,12
BIONOLLE 1020MD	0,77	240	50	5	947	3017	64,2	11	2,07

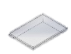
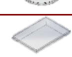
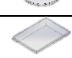
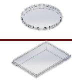
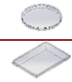
Two of the materials that have achieved a low thickness by conventional injection moulding, Purell and Pro-Fax Ultra, have not improved their designs by means of injection-compression and their required pressures for the thicknesses obtained by conventional injection moulding are over 1000 bar, 1080 bar in the case of Purell and 1113 in the case of Pro-Fax Ultra. Both materials have previously achieved a great reduction of their thicknesses, so further improvements are difficult to reach.

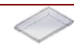
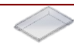
Ingeo 3251D offers good Results in all the evaluated parameters. Regarding functionality, its distortion value is 0,5 and sustainability parameter *g/ch* is 2,2 lower than the one obtained for the original geometry of 3,4, so the improvement is notorious. Other materials exhibit also good sustainable parameter values such as Bionolle or Mirell, but their distortion values are quite high, reason why their functionality can not be assured. On the other hand, Ingeo 3052D has not such a good sustainability parameter value of 3, but its distortion values are really good and it could be taken into consideration as an alternative.

5. Conclusions

Table 6 shows a summary of results based on which the following conclusions can be addressed:

Table 6. Summary of simulation results for original and circular geometry by conventional injection moulding and for circular geometry by injection compression

Material	Process	Geometry	Thickness [mm]	Mass [g]	Maximum pressure [bar]	Distortion [mm]	g/ch
Styrolution PS 165 N/L	Conventional injection moulding (Standard temperature conditions)	Original	1,4	83,08	1138	0,58	3,46
	Conventional injection moulding T_{max}		0,8	49,21	2256	0,66	2,05
			0,66	52,26	3578	1,23	1,69
	Injection-compression T_{max}		0,6	44,39	4439	0,5	1,43
Ingeo 3052D	Conventional injection moulding T_{max}		1,3	90,75	2429	2,83	3,78
			1,1	96,97	3625	0,98	3,13
	Injection-compression T_{max}		1,1	91,7	2543	2,8	2,96
Ingeo 3251D	Conventional injection moulding T_{max}		1	70,75	2348	1,13	2,95
			0,84	74,65	3825	0,72	2,41
	Injection-c ompressionT_{max}		0,8	68,4	2384	0,5	2,2
Ingeo 6202D	Conventional injection moulding T_{max}		1,3	90,76	2257	2,23	3,78
			1,16	102,1	3663	0,98	3,29
	Injection-compression T_{max}		1,16	96,92	2516	2,7	3,12
Mirel P1004	Conventional injection moulding T_{max}		1,3	92,71	2253	1,28	3,86
			1,09	97,65	3515	1,84	3,15
	Injection-compression T_{max}		1	84,82	2458	5,3	2,74
Purell EP	Conventional injection moulding		0,9	45,26	2106	1,76	1,89

274P	T_{max}		0,71	46,28	3175	0,6	1,49
	Injection-compression T_{max}		0,71	42,79	3503	2,74	1,38
Pro-Fax Ultra SC973	Conventional injection moulding		0,6	31,05	2509	1,48	1,3
	T_{max}		0,5	35,04	3589	1,06	1,12
	Injection-compression T_{max}		0,5	-	-	-	-
Bionolle 1020MD	Conventional injection moulding		0,9	61,72	2513	10,78	2,57
	T_{max}		0,77	68,12	3600	5,47	2,2
	Injection-compression T_{max}		0,77	64,19	3017	11	2,07

Regarding the original geometry design, all the further designs have improved the sustainability parameter. Redesign including injection-compression manufacturing process exhibit a higher improvement in this parameter. Biopolymers are the most respectful option with the environment, so thanks to excellent biodegradability Ingeo 3052D, 3251D and 6202D more sustainable alternatives from the point of view of materials origin.

On the other hand, with regard to the thickness reduction and so, mass reduction, Pro-Fax Ultra SC973 is capable of achieving a redesign with a thickness of 0.5 millimetres, according to simulation analysis. However, such a low thickness is quite rare to find in commercial applications, therefore a further detailed analysis should be carried out to make sure the practical viability of this redesign option.

Regarding functionality and quality of the packaging, distortion values are generally lower when injection- compression is applied. This is a low pressure process that eases a more uniform material distribution leading to a reduction of residual stresses, and so lower distortion. Ingeo 3251D reaches the lowest value of distortion, 0,5 millimetres.

An alternative redesign taking into account sustainability, and functionality could take Ingeo 3251D as material and injection-compression as manufacturing process. Under maximum temperature conditions a thickness of 0,8 millimetres (-0,6 mm regarding the original design) can be achieved. It implies a sustainability parameter value of 2,2 g/ch, better than the value of 3,4 g/ch obtained for the original design which implies a very efficient way of using the material required for the packaging.

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References

Aliotta, L ., Sciara, L. M., Cienlli, P., Canesi, I., Lazzeri, A. (2022). Improvement of the PLA Crystallinity and Heat Distortion Temperature Optimizing the Content of Nucleating Agents and the Injection Moulding Cycle Time. *Polymers*, 14(5):977

Albanna, M. (2011). Solid Waste Management Options and their Impacts Climate Change an on Human Health. In: *Environmental Protection Strategies for Sustainable Development Strategies for Sustainability, (pp. 499-528)*. Dordrecht: Springer. https://doi.org/10.1007/978-94-007-1591-2_16

Coppola, G., Gaudio, M. T., Lopresto, C.J., Calabró, V. (2021). Bioplastic from Renewable Biomass: A Facile Solution for a Greener Environment. *Earth Sys. And Env.*, 5(24)

Fernández, Á., Javierre, C., González, J., & Elduque, D. (2013). Development of Thermoplastic Material Food Packaging Considering Technical, Economic and Environmental Criteria. Journal Of Biobased Materials And Bioenergy, 7(2), 176-183. https://doi.org/10.1166/jbmb.2013.1323

Körber, S ., Moser, K., Diemert, J. (2022). I Development of High Temperature Resistant Stereocomplex PLA for Injection Moulding. *Polymers*, 14(3):384

Lin, C. M., Lin, Y. Q. (2023). Injection-compression moulding process on optical quality optimization of plastic lens array. *Polym. Adv. Tecnol.*, 34(11):3569–3585.

Dolge, K., Azis, R., Lund, P.D., Blumberga, D. (2021). Importance of energy efficiency in manufacturing industries for climate and competitiveness. *Environ. Clim. Technol.*, 25(1):306-317). https://doi.org/10.2478/rtuect-2021-0022.

European Parliament, 2020. *Communication from the commission to the European Parliament, the council, the European Economic and Social Committee and the Committee of the Regions. A new Circular Economy Action Plan for a cleaner and more competitive Europe.*

Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2020%3A98%3AFIN

Geueke, B., 2014. *Dossier – Bioplastics as food contact materials.* Retrieved from https://www.foodpackagingforum.org/fpf-2016/wp-content/uploads/2015/11/FPF_Dossier06_Bioplastics.pdf

Samalens, F., Thomas, M., Claverie, M., Castejón, N., Zhang, Y., Pigot, T., Blanc, S., FErnandes, S. (2022). Progresses and future prospects in biodegradation of marine biopolymers and emerging biopolymerbased materials for sustainable marine ecosystems. *Green. Chem.*, 24:1762-1779.