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The Financial Impact and Techno-economic Assessment of Bioplastics Based on Their Properties

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Abstract: *This study has proved the value of the bioplastics in replacing the classical polymers used for various applications by employing a new and original econometric model which underlines the interdependence between the bioplastics price and the following mechanical properties: Young modulus, Tensile strength and Elongation at break. The model was applied for 5 different bioplastics: polylactic acid (PLA), cellulose acetate (CA), poly (butylene succinate) (PBS), Bio-polyethylene (Bio-PE) and Bio-polyethylene terephthalate (Bio-PET). The biopolymers cover a large range of bioplastics both biodegradable and non-biodegradable. The developed model was run on Gretl software using the OLS (ordinary least squares) method. The residuals values are acceptable which means that the interdependence model fitted well the known data. Among all bioplastics studied, polylactic acid (PLA) exhibits the best constants in terms of reproducibility. All the regression equations obtained for the econometric study offer the possibility of forecasting the price for any other sort of bioplastic and it is a useful tool for assessment the financial impact of a bioplastic.*

Keywords*: bioplastics, financial impact, techno-economic assessment*

1. Introduction

Plastics are very important in modern life since they played important roles in food, healthcare, transportation, energy, medicine, etc. Also, these types of materials are influenced directly the sustainability of various processes like fuel efficiency of aeroplanes and cars by using lightweight plastics, energy saving by employing plastic insulators, advanced food packaging with increased shelf life thus reducing the food waste as well as the performance in medicine through plastic composites for controlled drug delivery systems, implants with improved mechanical properties and biocompatibility, etc. [1]. The plastics are produced in huge quantities every year (nearly 390 million tonnes) and consequently the plastic wastes are significant (approx. 6300 million tonnes since 1950). It must be considered also the annual growth rate of plastics which has increased to 4% in the last years [2, 3]. Therefore, in the last 10 years it was developed a high concern at the level of specialists and society towards the environmental impact of plastic wastes which leads to the new concept of circular plastic economy. This approach refers to minimizing the waste production as well as the use of non-renewable resources and in the meantime to increase the recycling and reuse capacities for plastics.

Most of the commercial's plastic materials are produced starting from fossil resources but now the raw materials tend to be replaced with renewable resources which finally give bioplastics. Thus, the monomers are obtained from biomass mixtures like sugars in plants and then they are polymerized to give similar polymers as classical plastics e.g., polyethylene bio-based or new polymers like polyhydroxyalcanoates. Therefore, the term bio-based refers to the material which is produced totally or partially from plants (biomass) such as sugarcane, wood, corn, etc. [4]. The bio-based plastics may be either biodegradable or non-biodegradable. The biodegradation process depends both on the plastic properties and environmental parameters like humidity, temperature, etc. Thus, the biodegradable capability does not depend on the raw material employed for synthesis but is rather connected to the chemical structure. Consequently, there are bio-based plastics which are not biodegradable and there are some plastics obtained from fossil which are biodegradable under special conditions (Figure 1).

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Bioplastics can be further detailed in description considering the bio suffix if they are produced from renewable resources for example bio-based polypropylene (Bio-PP). This is obtained from biomass derivatives, but its biodegradability is low. There are examples of plastics which are both biodegradable and bio-based like polyhydroxyalkanoates (PHAs). On the opposite there may be fossil-based plastics which may suffer biodegradation like polybutylene succinate (PBS).

Bioplastics may offer a large circularity by employing non-fossil resources, a low carbon footprint, enhanced properties, and an alternative end-of-life (EOL) through biodegradation [5].

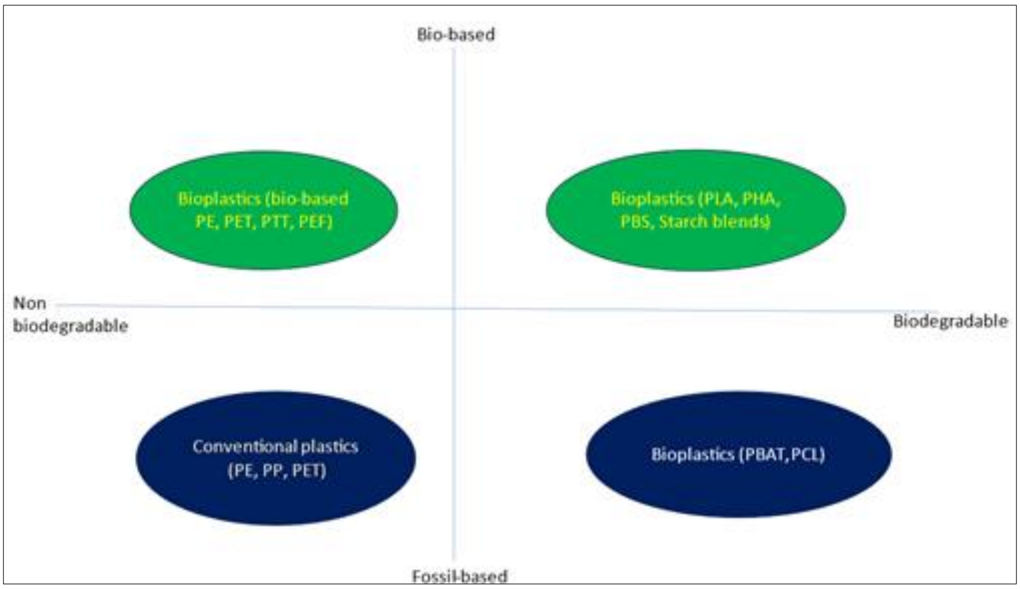

Figure 1. The classification of conventional plastics and bio-plastics concerning the raw sources and the biodegradability [4, 5] (PTT=Polytrimethylene terephthalate, PEF= polyethylene furanoate)

Generally, there were identified more than 20000 biobased products excluding food, feed and fuel [7]. These can be classified into various groups (Table 1). Golden and Handfield [6] reported an extensive categorization of the bio-based products into 6 groups linked with the types of application: chemicals, pharmaceuticals, enzymes and microorganisms, dyes, consumer products, biofuel co-products. The various end uses suggest a large range of applications in services and daily goods.

The extensive used of bio-based products will lead to the reduction of the petrol consumption by replacing the petrol-based products as well as to the reduction in use of fossil-based products and consequently to the diminishing of carbon emissions. For example, it was calculated that by using 15 different bio-based chemicals worldwide by employing corn starch as feedstock and all the petro-chemicals based to be replaced, approx. 512 million MT carbon dioxide/year will be saved until 2030 [9]. The advantages of using bio-based products and especially bioplastics consist not only in decreasing the carbon footprint but also a low toxicity and a significant contribution to a sustainable development through the property of biodegradability.

Many countries around the world have implemented adequate strategies to develop significant programs for bio-based products as well as to increase research for discovering new bioplastics with targeted applications. The global market size for biobased industry was estimated to about 10.3 trillion USD in 2018 including feed and food sectors. If the food and feed branches are excluded the overall bio-based industry was valued to 3.4 trillion USD in 2018 with a forecasting of increasing rate of about 50% [10] (Table 2). Of course, this rate could be even higher if the pressure of global warming will determine the governments to take urgent measures to partially cancel the effects of continuously using fossil-based raw materials for production of everyday goods including plastics for various applications which contribute to a high carbon evolving into the atmosphere.

Table 1. The connection between end uses of bio-products and the main categories of these products (excluding feed, food, pharmaceutics, energy) [8]

Types of bio-products	End uses
1. Chemicals 1.1. Biopolymers 1.1.1. Derived from polysaccharides like starch or chitin 1.1.2. Produced from chemical synthesis using renewable monomers like polylactic acid PLA 1.1.3. Produced by microorgansims or modified bacteria like polyhydroxyalcanoates (PHAs) 1.2. Bioplastics like polylactic acid (PLA), polyhydroxyalcanoates (PHAs), fatty acids (FA), plant oils, fatty acid methyl esters (FAME) 1.3. Biosurfactants 1.4. Biosolvents 1.5. Biolubricants 2. Biofuel co-products 3. Microorganisms and enzymes 4. Dyes and inks 5. Biopharmaceuticals	1. Films and packaging 2. Food services 3. Household supplies 4. Ground maintenance 5. Feedstock 6. Miscellaneous 7. Personal care and toiletries 8. Safety equipment 9. Maintenance of equipment and vehicle 10. Office supplies

Table 2. Predicted bioeconomy market size, 2018-2030 [11]

Industries	Market size, billion USD		
	2018	2030	Compound Annual Growth Rate (%)
All biobased industries	0.1388	15.151	0.056
All biobased industries, excluding feed and food	3430	5054	3.3
Pharmaceuticals	264	760	9.2
Buiding materials and construction	331	682	6.2
Packaging	375	544	3.2
Electronics and electrical products	117	217	5.1
Motor vehicles and components	255	526	6.2

Bioplastics production represents less than 1% of the whole plastics industry [4]. However, the bioplastics industry continues to growth due to the increased demand for replacement of fossil-based plastics as well as to public awareness in the world to change to a circular economy with the aim of a future totally sustainable planet. Also new applications of bio-based plastics were settled with increased efficiency and lower costs [12].

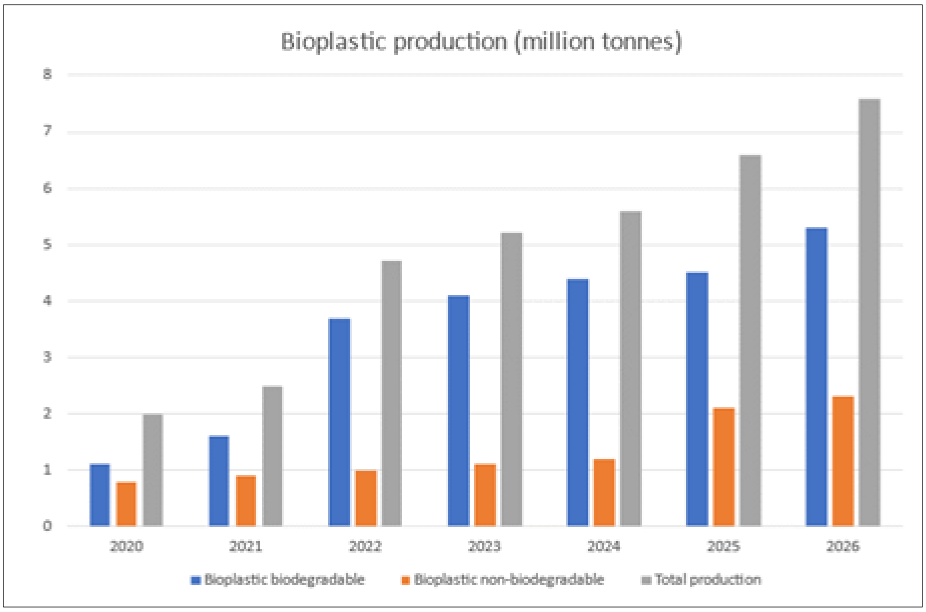

Figure 2. The forecast of worldwide bioplastic production [12]

It can be noticed from Figure 2 that the production of biodegradable bioplastics will increase with a higher rate than that of non-biodegradable ones which reflects the strong need for a sustainable development of applications based on plastics and integration of bioplastics within a circular economy.

Regarding the types of bioplastics which are produced today, the largest one is polylactic acid (PLA) with nearly 21% from the total market, followed by starch blends and polyethylene (Figure 3). This aspect should be also considered in correlation with the main applications of various bioplastics (Figure 4) [13].

Biobased plastics such as biobased PE or PET exhibit similar properties like conventional PE or PET but the main advantage is that they can be easily recycled by mechanical approach and in the meantime, they determine a significant reduction in the carbon footprint. Therefore, the bioplastics industry had to provide innovative technical solutions for synthesis and processing of these materials sometimes also considering the efficiency ad final output of the processes. Moreover, many of the bioplastics show new properties and an enhanced performance like increased mechanical strength, better optical properties as well as a reduced size and weight especially a reduced thickness. Thus, there were made innovative solutions to produce PHA, PLA or biobased PBS which are biodegradable in certain conditions and thus making a full approach to the concept of circular economy. One of the most challenge property for plastics is given by the barrier properties type and in this case new materials like polyethylene furanoate (PEF) were discovered and exhibiting the advantage of being easily recycled by special mechanical procedure. But still the main asset of the bioplastics is to reduce the dependency on the limited fossil resources and to significantly decrease the gas emissions.

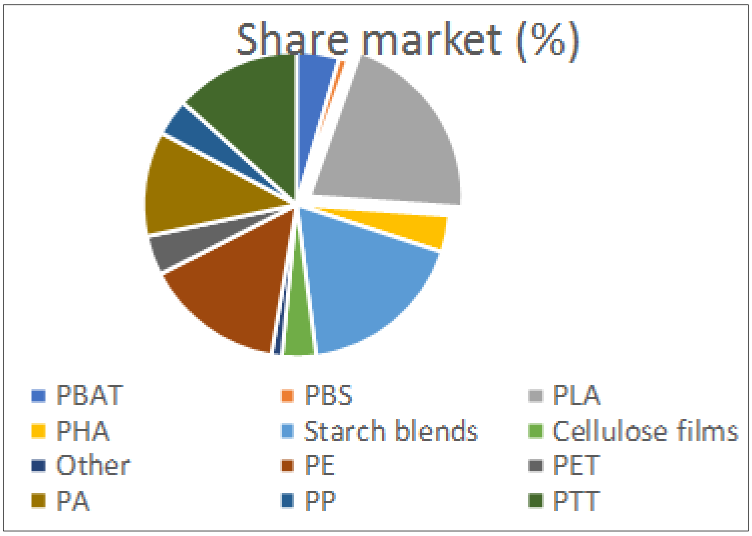

Figure 3. Share market for various bioplastics [4]

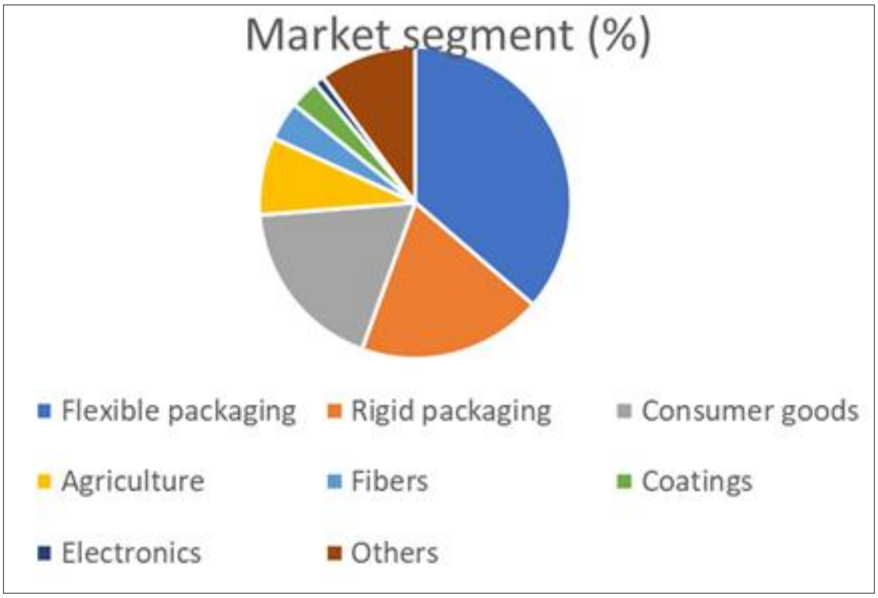

Figure 4. Market segment for bioplastics [4]

Bioplastics may be produced from primary feedstocks like corn, sugarcane, wheat, soy, rice beet, and potatoes [12]. Some bioplastic types are obtained directly from polymers which are naturally developed in plants and microbes [14]. Also, cellulose-based materials may be used as a raw material for synthesis of bioplastics but most of the bioplastics are produced through synthetic methods employing three major approaches: polymerization of a bio-monomer, modification of naturally existing polymer and complex extraction from microorganisms. Thus, the most common bioplastics produced through these methods are: cellulose acetate (CA), starch-based polymers (SBPs), polylactic acid (PLA), polybutylene succinate (PBS), bio-based polyethylene (Bio-PE), bio-based polyethylene terephthalate (Bio-PET).

2. Materials and methods

2.1. Materials

To reach the goal of transition to a full circular economy it is important to clear what properties of the new bio-based products may be similar with that for the classical materials produced from fossil-based resources. Therefore, detailed technical datasheets are required for the mechanical, thermal, electrical and barrier properties of the new bioplastics.

For our study we have chosen 5 different types of bioplastics with the aim of covering all the categories of bioplastics produced today: polylactic acid (PLA), cellulose acetate (CA), poly (butylene succinate) (PBS), Bio-polyethylene (Bio-PE) and Bio-polyethylene terephthalate (Bio-PET). The tensile properties of these commercially available bioplastics are shown in Table 3.

Table 3. The tensile properties of bioplastics included in this study [14]

Polymer	**Mechanical properties**		
	Young's modulus (MPa)	Tensile strength (MPa)	Elongation at break (%)
CA	4388	44.2	4.3
Bio-PE	1729	21.6	40
PBS	631	42.2	275
Bio-PET	2273	59.4	736
PLA	3435	74.4	7.8

The flexural properties of the considered bioplastics are listed in Table 4.

Table 4. The flexural properties of bioplastics included in this study [14]

Polymer	**Flexural properties**		
	Flexural modulus (MPa)	Flexural strength (MPa)	Deformation at break (%)
CA	4550	69.4	4.9
Bio-PE	855	26.2	>12
PBS	602	35	>12
Bio-PET	2337	88.2	>12
PLA	3198	107.9	8.2

The impact properties of the bioplastics considered in this study are revealed in Table 5 [14]

Table 5. The impact properties of bioplastics included in this study [14]

Polymer	**Flexural properties**		
	Charpy Impact Resistance (MPa)	Hardness shore A (MPa)	Hardness Shore D
CA	1.8	100	83.4
Bio-PE	3.6	100	57.4
PBS	12.6	96.1	65.1
Bio-PET	3.1	100	76.1
PLA	2.1	100	81.8

2.2. Methods

The present method focused on the developing of an original model for the development of a financial impact study for replacement of the fossil-based polymers with bioplastics which considers the main mechanical properties of the industrial bioplastics and correlates the final price of the products with the advanced tensile properties of these materials.

Three categories of mechanical properties were considered for the regression method:Young modulus, Tensile strength and Elongation at break. Moreover, the correlation between the final price of the bioplastics and the ability of biodegradation was estimated through this method which gives an output for the environmental impact of these materials.

The data were introduced into an econometric efficiency model, developed by GRETL software.

Gretl is an open-source statistical package, mainly for econometrics. The name is an acronym for Gnu Regression, Econometrics and Time-series Library. It has both a graphical user interface (GUI) and a command-line interface. It is a statistical technique for identifying the relationship between a single independent variable and a dependent variable. The equation for simple linear regression is given as: $Y = a+b \times X$ where a and b are the coefficients, Y is the dependent variable and X is the independent variable. It includes natively all the basic statistical techniques employed in contemporary Econometrics and Time-Series Analysis. Gretl has been reviewed several times in the Journal of Applied Econometrics [15] and, more recently, in the Australian Economic Review [16].

3. Results and discussions

A detailed analysis of the environmental properties of the studied bioplastics must consider first the biodegradation capability. Generally, the polymers with aliphatic ester bonds are more available for biodegradation in comparison with the durable polymers which are resistant to enzymatic and non-enzymatic hydrolysis like amides, aromatic esters, and those with C-C bonds [5]. The second aspect to consider is the direct influence on the global warming through the assessment of the global warming potential (GWP). These two significant indicators for the environmental impact are correlated with the price of the studied bioplastics since this is an important criterium for determining the financial impact of the bioplastics already available on the market (Table 6).

Table 6. The environmental properties and typical prices of the studied bioplastics [5]

Bioplastic	**Environmental properties**			**Price (US$/kg)**
	Biodegradation (industrial)	Biodegradation (ocean)	GWP (tone CO2 eq. per ton polymer)	
Bio-PET	NA	NA	2-5.5	1.2
Bio-PE	NA	NA	0.68	1.8-2.4
PBS	2-5 months	> 1 year	NA	4.0
PLA	6-9 weeks	> 1.5 years	0.5-2.9	2.0
CA	6-9 weeks	> 1 year	0.8-2.2	5.0

An enlarge analysis of the prices of the studied bioplastics shows that even the PLA price has significantly fallen in the last years it is still not competitive with classical plastics. The production of PBS is currently based on fossil resources due to the lack of availability for bio-based succinic acid. For Bio-PE the raw materials costs represent the most significant part of the total production costs. Therefore, the availability and price of the raw materials are the most important indicators for starting a Bio-PE plant. In the case of Bio-PET the production capacities are expected to highly increase in the next years since Coca Cola set up an expressed goal to switch to a fully bio-based bottle soon.

The financial impact of replacing classical plastics with the studied bioplastics has considered the correlation between the prices and the mechanical properties: Young modulus (MPa), Tensile strength (MPa) and Elongation at break (%). The data sets used for the econometric model are aggregated from those listed in Table 3 and Table 6 and presented in Table 7.

Table 7. The data sets used in the econometric study

No of observation	**Bioplastic**		**Mechanical properties**		
		Price (USD $/kg)	Young's modulus (MPa)	Tensile strength (MPa)	Elongation at break (%)
1	CA	5.0	4388	44.2	4.3
2	Bio-PE	2.3	1729	21.6	40
3	PBS	4.0	631	42.2	275

No of observation	Bioplastic		Mechanical properties		
		Price (USD $/kg)	Young's modulus (MPa)	Tensile strength (MPa)	Elongation at break (%)
4	Bio-PET	1.2	2273	59.4	736
5	PLA	2.3	3435	74.4	7.8

All the data sets were analyzed with OLS (ordinary least squares) model. The results for the dependence of price of the bioplastics on the Young modulus value are presented in Table 8 and Figure 5.

Table 8. OLS, using observations 1-5
Dependent variable: price

	Coefficient	*Std. Error*	*t-ratio*	*p-value*
const	2.34356	1.68766	1.389	0.2591
Youngm	0.000223363	0.000599622	0.3725	0.7343

Mean dependent var	2.900000	S.D. dependent var	1.555635
Sum squared resid	9.252059	S.E. of regression	1.756138
R-squared	0.044209	Adjusted R-squared	-0.274388
F(1, 3)	0.138761	P-value(F)	0.734276
Log-likelihood	−8.633213	Akaike criterion	21.26643
Schwarz criterion	20.48530	Hannan-Quinn	19.16997

The OLS model also gives the confidence intervals and the residuals (the difference between the predicted values and the real ones). The confidence intervals are marked with blue color and the fitted graph according to the model with red color in Figure 5.

The parameters listed in Table 8 may be related to the other set of data considering the following properties: tensile strength and elongation at break. A lower P-value means that the economic parameters are superior so that a better model is obtained.

The values obtained for data set concerning the influence of Tensile strength towards the price of the bioplastics are presented in Table 9 and Figure 6 and the values for data set regarding the influence of the Elongation at break against the bioplastics price are shown in Table 10 and Figure 7.

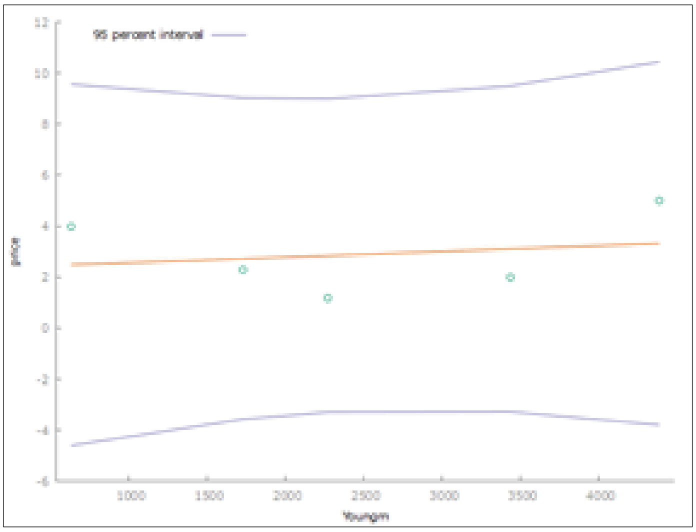

Figure 5. The dependence of the bioplastics price on the Young modulus values

Table 9. OLS, using observations 1-5
Dependent variable: Price

	Coefficient	*Std. Error*	*t-ratio*	*p-value*
const	4.18216	2.19686	1.904	0.1531
Tensiles	−0.0265129	0.0426518	−0.6216	0.5782

Mean dependent var	2.900000	S.D. dependent var	1.555635
Sum squared resid	8.575474	S.E. of regression	1.690707
R-squared	0.114104	Adjusted R-squared	-0.181195
F(1, 3)	0.386402	P-value(F)	0.578234
Log-likelihood	−8.443363	Akaike criterion	20.88673
Schwarz criterion	20.10560	Hannan-Quinn	18.79027

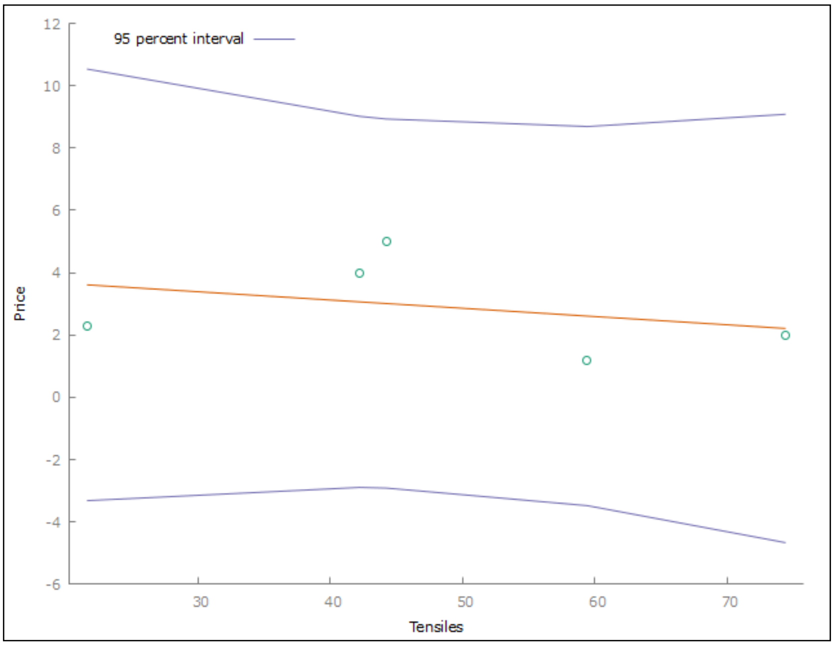

Figure 6. The dependence of the bioplastics price on the Tensile strength values

Table 10. OLS, using observations 1-5
Dependent variable: Price

	Coefficient	*Std. Error*	*t-ratio*	*p-value*	
const	3.42521	0.874491	3.917	0.0296	**
Elongation	−0.00247018	0.00248539	−0.9939	0.3935	

Mean dependent var	2.900000	S.D. dependent var	1.555635
Sum squared resid	7.282226	S.E. of regression	1.558014
R-squared	0.247704	Adjusted R-squared	-0.003061
F(1, 3)	0.987792	P-value(F)	0.393542
Log-likelihood	−8.034689	Akaike criterion	20.06938
Schwarz criterion	19.28825	Hannan-Quinn	17.97292

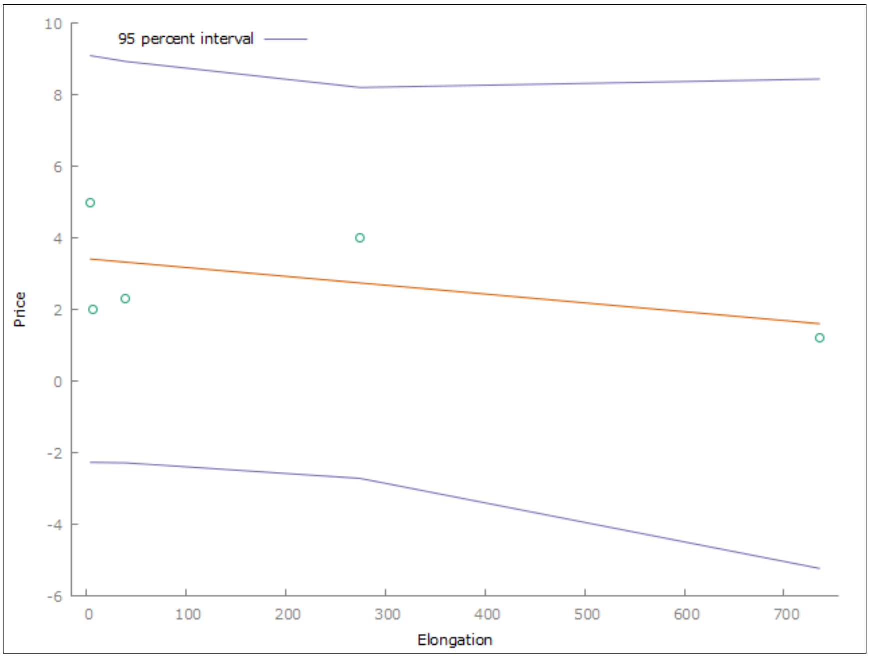

Figure 7. The dependence of the bioplastics price on the Elongation at break values

The const values from Tables 8, 9, and 10 are the values of "a" parameter from the equation of linear regression.

4. Conclusions

This study has proved the value of the bioplastics in replacing the classical polymers used for various applications by employing a new and original econometric model which underlines the interdependence between the bioplastics price and the following mechanical properties: Young modulus, Tensile strength and Elongation at break. The model was applied for 5 different bioplastics: polylactic acid (PLA), cellulose acetate (CA), poly (butylene succinate) (PBS), Bio-polyethylene (Bio-PE) and Bio-poly-ethylene terephthalate (Bio-PET)**.** The biopolymers cover a large range of bioplastics both bio-degradable and non-biodegradable.

The developed model was run on Gretl software using the OLS 9ordinary least squares) method. The residuals values are acceptable which means that the interdependence model fitted well the known data. Among all bioplastics studied, polylactic acid (PLA) exhibits the best constants in terms of reproducibility. All the regression equations obtained for the econometric study offer the possibility of forecasting the price for any other sort of bioplastic and it is a useful tool for assessment the financial impact of a bioplastic.

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