ppDOI: 10.2507/35th.daaam.proceedings.xxx

MANUFACTURING METHOD AND CHARACTERIZATION OF A NUMBER OF THERMOPLASTIC COMPOSITE MATERIALS WITH NATURAL FIBRES

Cornel Ciupan, Emilia Ciupan & Mihai Ciupan

This Publication has to be referred as: Ciupan, C[ornel]; Ciupan, E[milia] & Ciupan, M[ihai] (2024). Manufacturing Method and Characterization of a Number of Thermoplastic Composite Materials with Natural Fibers, Proceedings of the 35th DAAAM International Symposium, pp.xxxx-xxxx, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-xx-x, ISSN 1726-9679, Vienna, Austria
DOI: 10.2507/35th.daaam.proceedings.xxx

Abstract

The furniture industry is one of the world's most important sectors, but due to the scarcity of wood and its high-cost companies have had to look for alternatives. Natural fibre composites represent one alternative because many fibrous plants are easy to cultivate and generate high yields. The authors have also developed a simple and cost-efficient way of blending natural fibres and polypropylene and forming them into boards needed for samples in laboratory testing. The paper studies the mechanical properties of several natural fibre composites which incorporate hemp, willow or jute. The authors developed and tested several formulations consisting of one type of natural fibre (hemp, willow and jute) with varying percentages of polypropylene as thermoplastic matrix. The tests show that below a certain percentage of matrix material, the composite loses its mechanical properties quickly. However, certain natural fibre and polypropylene blends resulted in good mechanical properties and indicated excellent potential for use in the structural elements of furniture.

Keywords: natural fibre composites; thermoplastic matrix; sample manufacturing method.

1. Introduction

The furniture industry is one of Romania's strategic branches. In 2023, it brought a contribution of 1.23 billion euros to Romania's trade balance. It represents the second economic branch as added value. From the amount of furniture produced in Romania, 90% is exported, Romania ranking as the 5th country in Europe, and the 12th in the world, from this point of view [1].

However, furniture manufacturing in Romania has decreased significantly for the last two years. One of the important factors that contributed to this is the steady increase, for the last eight years, of the price of wood on the local market, which has led to decreased competitiveness on the international market. The decrease of furniture manufacturing resulted, in 2023, in a reduction by 19% of the number of employees hired in the furniture sector, as compared to 2022.

Finding advantageous alternative solutions to the replacement of the main raw material—wood—can contribute to a revival of the steady growth of this economic sector. A solution in this sense is the use of composite materials made of natural fibre (flax, hemp, willow, poplar, coconut, etc.), mixed with other matrices.

1.1. Advantages of using thermoplastic composite materials with natural fibres

The industry of upholstered furniture, as a branch of the furniture industry, uses, to a large extent, wood, chipboard, multi-layered and other wooden boards, polyurethane, non-woven materials, textile materials, and leather and substitutes of leather. Natural resources are limited. In the current situation in which the world is facing environmental degradation and global warming, rethinking the design process of products or services is of major interest in all fields of activity. Some authors propose the adoption of an eco-design process that reconsiders the entire life cycle of products or services [2]. At the same time, there are concerns about the classification, evaluation and ranking of the negative effects that an organization can produce on the environment, in accordance with the ISO 14001 standard [3].

Under these circumstances, the partial replacement of wood and wood-based products in the structure of an item upholstered with composite materials with matrices from polypropylene, or adhesives and natural fibres, as fibres of enforcement, has a significant number of advantages. Among them count the preservation of the current forests, the reduction of pollution and of the greenhouse emissions, the preservation of flora and fauna, increased productivity of the fibre-producing cultures, and reduced costs [4], [5], [6]. The use of the new materials contributes to the development of a more competitive upholstered industry, and to an increased number of jobs.

For a cubic meter of wood utilized in the upholstered industry, around six cubic meters of raw wood must be cut down from the forest. While for a hectare of forest, the quantity of wood grows by 3-5t/year, the production of natural fibres per hectare is larger, namely 10-14 t/ha, for hemp, 50-60 t/ha, for willow and poplar, 16-20 t/ha, for miscanthus.

The "environmental friendliness" of the composite material is also given by the biodegradability of the natural fibres, their origin from renewable sources, and the chances of recycling the material [7], [8], [9]. Furniture factories must comply with the Forest Stewardship Council (FSC) requirements, which impose awareness of wood traceability and responsible management of forests worldwide.

The interest and necessity of replacing certain wooden parts in the structure of upholstered furniture, without affecting the external appearance of the product and its functional requirements, were presented in more detail in papers [4] and [10].

Criteria	Wood/Chipboard	Composite materials
Excessive use of wood	Yes	No
Raw material availability	Lengthy harvesting cycle (80-100 years) and little annual growth (3-5 t/ha/year)	Yearly harvesting and renewal, and significant yearly growth (50-60 t/ha/year, in the cases of willow and poplar)
Material usage yield	Low	Significant
Complex-shaped items	Involves a wide range of frames and types of raw materials. Example: an armchair side uses 21 elements and 3 types of raw material (wood, chipboard, cardboard)	Reduced number of frames and the possibility of using a single raw material. Example: an armchair side can be made of 2 elements of composite material
Technological complexity	It is difficult to realize complex shapes, with many manual operations for the realization of the frames and assembly	It is easy to realize complex spatial shapes through thermoforming or injection in moulds
Dimension of the technological line	Large surface both at the producer of raw material and the one of the frames, as it requires many operations of cutting, processing, assembling	A compact line and a short technological flow, which can be automated
Content of formaldehyde (carcinogenic substance)	Yes (Chipboard- 15%)	No
Purchase price of raw material	Price in a continuous growth	Slight variations, price stability
Recycling / reusage	Reduced	Excellent

Table 1. Advantages of using composite material

When traditional technologies are used, the manufacturing of an upholstered item involves the use of several wooden frames [4], higher manufacturing costs and a lengthier manufacturing process. The replacement of wood by natural fibre composite to obtain complex-shaped frames comes along with a number of advantages (Table 1).

1.2. Problem statement

The authors have specific achievements in the development of thermoplastic composite materials and their usage in the field of upholstered furniture, at TAPARO SA from Targu Lapus [4], [10], [11], [12]. A wide range of frames (sides of sofas, armchairs, chairs, etc.) were manufactured of composite materials made of a fibrous thermoplastic (polypropylene, with a length of 40-60 mm, and a linear density of 7-16 DEN, in percentages that ranged from 40% to 50% of the total weight of the mixture) and of natural fibrous component (fibres of hemp, jute, sisal, coconut, etc.), or a mixture of such fibres with a linear mass density of 70-80 DEN, and a length of the fibre between 5 and 100 mm, in a percentage between 50% and 60% of the total weight of the mixture. These materials are obtained as fibrous layers mechanically reinforced by interweaving. The transformation of the fibrous layer-shaped composite into frames is achieved through the following operations: cutting the material in accordance with the dimensions of the item, heating the material in a hot plate press at a temperature higher than the melting temperature of the matrix, transferring it into the thermoforming mould, and consolidating it through cooling.

From the research conducted [4], [13], the authors noticed that for the items to be competitive, the time necessary for the consolidation of the composite material into items should be reduced. For instance, the time necessary for the thermoforming of a piece with the dimension of a shell for an armchair is greater than 15 min. This cannot be reduced due to the extensive amount of time required in the mould, which is due, in its turn, to the reduced thermal transfer coefficient of the natural fibres.

A significant reduction of composite transformation time could be obtained by replacing the thermoforming technology with injection, which is used to obtain plastic products. Composite mixtures with long fibres cannot be used for injection, as this requires the use of short fibres, or granules.

For a new composite to be used industrially, it should be characterized, to determine its properties. The characterization of the material involves blending the raw materials and thermoforming several samples that should be submitted to mechanical trials on specialized machines [11], [14], [15], [16].

The authors developed a simple and effective method of obtaining new materials by using simple and cost-effective technological equipment.

2. Method and Equipment Presentation

To develop a simple and effective method of making and improving the natural fibre composite materials, the authors turned to using technological equipment of reduced complexity for both the obtaining of the fibrous mixture and the thermal consolidation of the samples. The characterization of the material is made on special machines, based on industry specific standards.

The method of making and characterizing the mixture formulations for the thermoplastic natural fibres composite materials involves the following stages:

A. Elaborating the material formulation:
   - choosing the constituents (natural fibres, thermoplastic matrix and their parameters)
   - elaborating the material formulations (proportion of the constituents)

B. Making the composite material and thermally consolidating it:
   - preparing the constituents
   - realizing the fibrous mixture
   - thermally consolidating it in the shape of boards using different process parameters

C. Characterizing the composite material:
   - cutting the samples out of the consolidated composite boards
   - characterizing the material by determining the tensile strength, Young's modulus, and elongation
   - interpreting the results and selecting the formulations that offer the most appropriate physical and mechanical properties.

2.1. Developing the material formulation

The goal of this stage is to establish the optimum percentage of thermoplastic fibre in the mixture, depending on the usage of the composite material. The percentage of polypropylene used should be as little as possible, given its higher cost, as compared to the natural fibre, and the negative impact on the environment.

Composite formulations can be made using virgin or recycled polypropylene to optimize the costs and use resources sustainably. However, the validation of a formulation can be made solely based on the characterization of the material. The technology of obtaining and consolidating the fibrous mixture should also be analysed when elaborating a formulation for use in series production.

Composite materials were made using different types of natural fibres. Three formulations were designed for each fibre material where the percentage of natural fibre and polypropylene differed. Similarly, formulations made of three elements (for example, hemp, willow and polypropylene) could be made, but the current paper focused on formulations containing just one type of natural fibre.

2.2. Making and thermal consolidation of the composite material

The first stage in the realization of the composite material consists in the preparation of the natural and polypropylene fibres at the required parameters. The second one involves weighing the right percentage of the constituents based on the formulation. Subsequently, the fibrous mixture is made whilst taking care to obtain good homogeneity.

In most of the applications of natural fibre composites, the fibrous mixture must be consolidated as a piece of textile, so that it can be easily cut and placed in the thermoforming mould. To simplify the method, a mould of reduced complexity was conceived, in which the material is placed directly, with no need of previous consolidation as a fibrous layer.

To thermally consolidate the fibres as a board, a mould was made consisting of the following parts: core 1, handle 2, pressing screws 3, cavity 4 and centring pins 5 (Fig. 1).

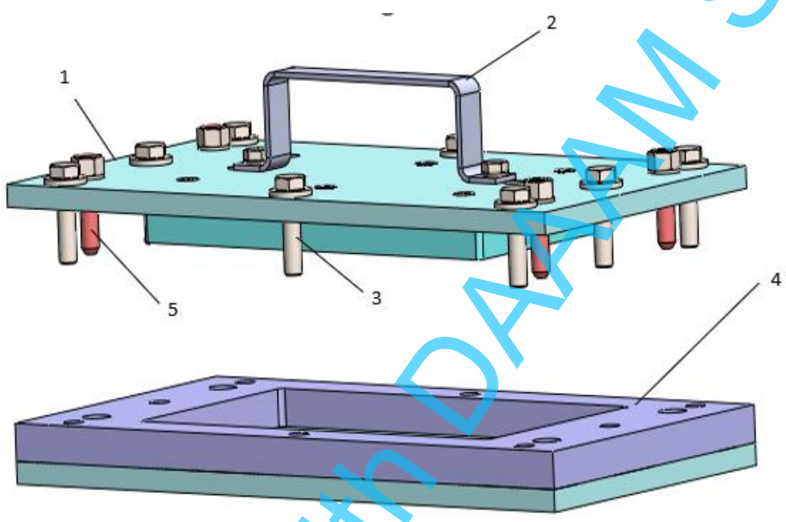

Fig. 1. Thermoforming mould

The composite mixture is placed in cavity 4 (Fig. 2). Afterwards, the mould is closed, and screws 3 are tightened to a torque of 5 Nm, which ensures a pressure of 10 MPa on the surface of the composite material. Thermoforming involves the heating of the mixture above the melting temperature of the polypropylene. The mould was placed in a convection oven (Fig. 2). The oven offers the possibility of regulating temperature (up to 240° C) and heating time (15-60 minutes). The oven is equipped with a thermometer for temperature control.

Fig. 2. Oven for thermoforming

The temperature of the oven and the heating time were established through experimental research and depended on the type of natural fibres and the thickness of the mixed layer.

2.3. Characterization of the composite material

The samples were cut from the thermally consolidated board and tested in terms of tensile strength through traction. The tensile strength, the specific elongation and Young's modulus were determined. The samples and tests were in accordance with standard ASTM D3039, "Test Method for Tensile Properties of Polymer Matrix Composite Materials".

3. Results

3.1. Composite material formulations

Nine formulations of material marked FS1-FS9 (Table 1) were elaborated using natural fibres of jute, willow and hemp.

No.	Vegetable fibre	Polypropylene [%]		
		50 %	40%	30%
1.	Jute	FS1	FS2	FS3
2.	Willow	FS4	FS5	FS6
3.	Hemp	FS7	FS8	FS9

Table 2. formulations of composite materials of short fibre

3.2. Making of the thermally consolidated boards

Natural and polypropylene fibres were prepared during the first stage. The natural fibres were acquired from several providers and were cut so that their length was between 1 and 5 mm (Fig. 3, Fig. 4).

willow coconut hemp jute cane

Fig. 3. Vegetable fibres

Virgin polypropylene | 70% willow-30% polypropylene | Cutting waste (hemp and polypropylene) | 50% hemp-50% recycled polypropylene

Fig. 4. Polypropylene fibre and mixture

The blends were prepared based on the formulations during the second stage. A scale with a precision of one gram was used to weigh the fibres and the blend was made manually (Fig. 5).

After some trials, the oven was set at a temperature of 220 °C as it was observed that at this temperature the blend reaches the temperature of 180 °C after a time of 45 minutes. At this temperature, the polypropylene is melted, and the natural fibre is not affected.

After being taken from the oven, the bolts of the mould are torqued again to 5 Nm, and then the mould is left to cool. After the temperature of the mould drops below 60 °C, the thermoformed board is taken out (Fig. 6, 7).

Fig. 5. Making the fibrous mixture and placing it in the mould

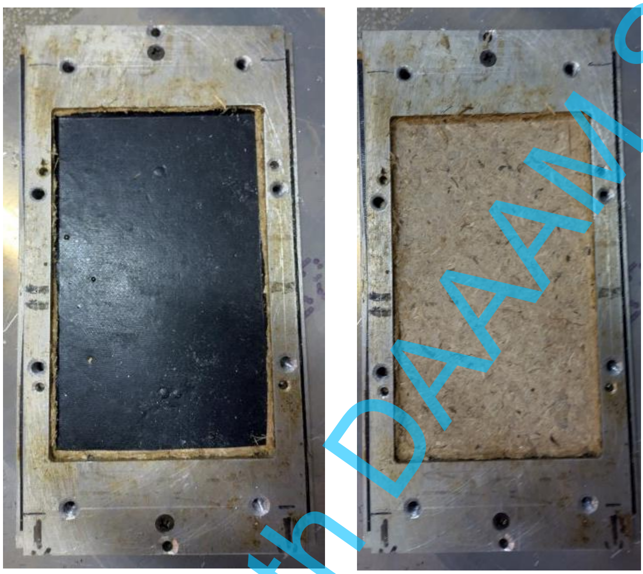

Fig. 6. Mould cavity with thermoformed board

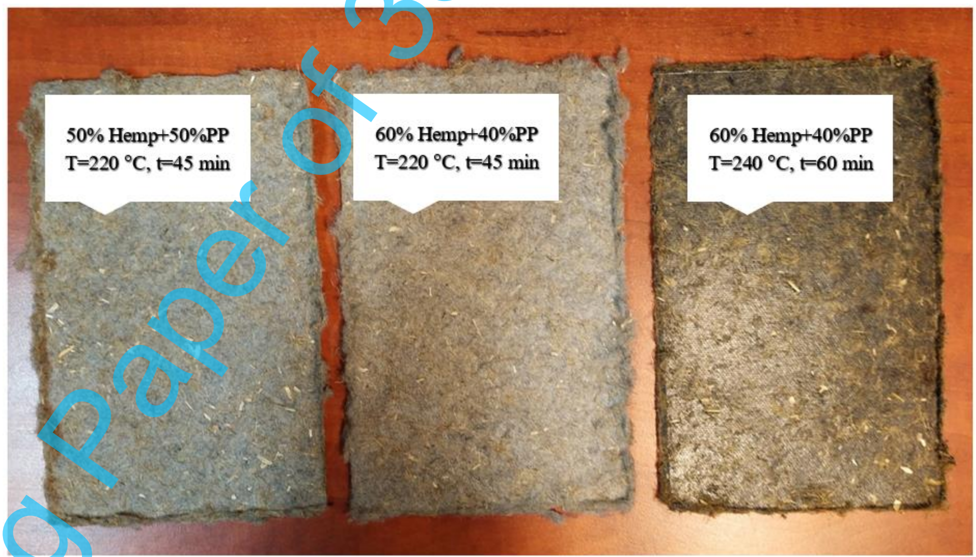

Fig.7. Thermoformed boards of hemp and polypropylene

3.3. Characterization of new materials

Five samples of each type of consolidated material were subjected to tensile testing. The machine Zwick/Roell Z150 from the CERTETA laboratory of the Technical University of Cluj-Napoca was used. Figure 8 shows the graphs from the Test report for material FS1.

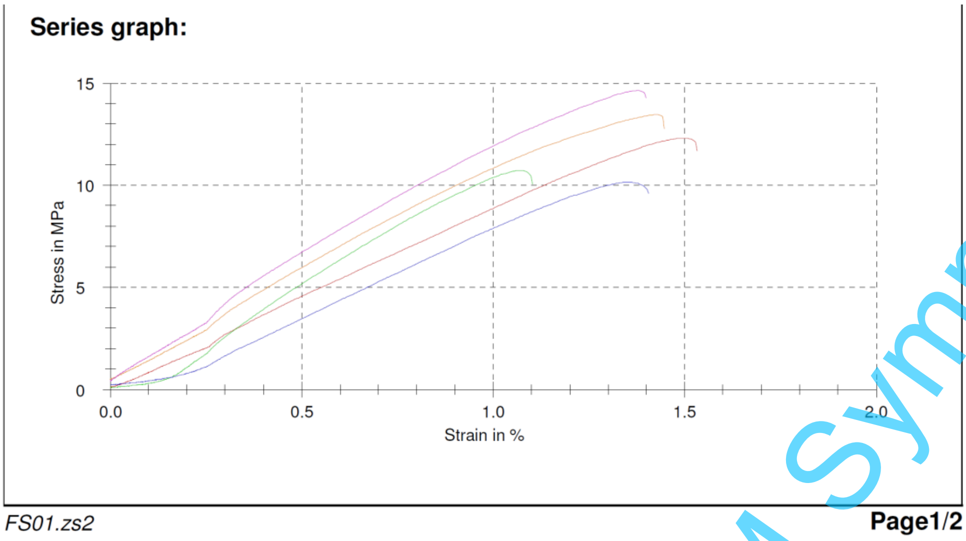

Fig. 8. Test report FS1

The following parameters were evaluated for each material formulation: tensile strength, specific elongation and Young's modulus. The results are shown in Table 3. The optimization regards the modification of the parameters of thermoforming, with the goal of reducing the percentage of polypropylene from the mixture, correlated with the physical and mechanical characteristics of the consolidated material and the decrease of the production cost per unit.

Nr. crt.	**Formulation**	**Medium density ρ[g/cm^3]**	**Ultimate tensile strength UTS [MPa]**	**Young's modulus E [MPa]**	**Elongation %**
1.	FS1 (jute 50%, polypropylene 50%)	0.66	12.30	845.0	1.30
2.	FS2 (jute 60%, polypropylene 40%)	0.51	5.80	423.0	1.30
3.	FS3 (jute 70%, polypropylene 30%)	0.47	5.69	362.0	1.30
4.	FS4 (willow 50%, polypropylene 50%)	0.51	5.17	446.0	1.10
5.	FS5 (willow 60%, polypropylene 40%)	0.52	5.03	4.23	1.10
6.	FS6 (willow 70%, polypropylene 30%)	0.51	4.86	417.0	1.20
7.	FS7 (hemp 50%, polypropylene 50%)	0.76	24.60	867.0	2.80
8.	FS8 (hemp 60%, polypropylene 40%)	0.74	17.90	942.0	2.20
9.	FS9 (hemp 70%, polypropylene 30%)	0.69	13.60	637.0	1.90

Table 3. Results obtained

4. Conclusion

The authors identified the need to replace wood in the structure of upholstered furniture with thermoplastic composite materials with plant fibres. To create new composite materials, it is necessary to try different formulations, and this cannot be done economically on the industrial production lines of the material.

To solve the problem, the paper presents a simple and effective method of elaborating and characterizing new formulations of composites made of natural fibres and a thermoplastic matrix, by using economic, reliable and easy-to-use technological equipment.

The analysis of the newly elaborated and consolidated materials by using the above-mentioned method leads to the following conclusions:

- The best results were obtained in the case of the composite mixtures that had hemp fibres. Material FS7 used short fibres with a blend of 50% hemp and 50% polypropylene and had mechanical properties like the material obtained from fibrous layers consolidated through interweaving and having the same amount of polypropylene.
- The materials of jute fibres and polypropylene have a tensile strength below 50%, as compared to hemp. The materials with willow and polypropylene have significantly reduced mechanical properties, as compared to those made of hemp and jute. This can be explained by the deterioration of the natural fibre when heated, and/or a much weaker bond between the consolidating fibres and the thermoplastic matrix. The strength of the composites with willow fibres is inferior to the other ones, since the fibres are very short and have a large number of particles.

With the proposed method, the authors will develop new composite materials using combinations of plant fibres (hemp with willow, flax with poplar etc.) and varying proportions with polypropylene fibres.

5. Acknowledgments

The paper resulted from research conducted in the project "The development of a research centre in the field of composite material at SC TAPARO SA", project code SMIS: 121434.

6. References

[1] https://www.zf.ro/business-construct/dumitru-blaga-presedintele-apmr-industria-mobilei-doilea-sector-22490378, (2024). Ziarul Financiar, Accessed on: 2024-09-20

[2] Bodur, O.; Walcher, E. M.; Durakbasa, N. & Sterca, D. A. (2021). Implementation of an Eco-Design Process to Minimize Negative Environmental Impacts – Case Study, Chapter 10 in DAAAM International Scientific Book 2021, pp.117-130, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-31-0, ISSN 1726-9687, Vienna, Austria, DOI: 10.2507/daaam.scibook.2021.10]

[3] Tomaskova, T. & Bicova, K. (2021). Impact of Machining on the Environment, Proceedings of the 32nd DAAAM International Symposium, pp.0623-0630, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734-33-4, ISSN 1726-9679, Vienna, Austria, DOI: 10.2507/32nd.daaam.proceedings.088

[4] Ciupan, E., Ciupan, C., Câmpean, E. M., Stelea, L., Policsek, C. E., Lungu, F., & Jucan, D. C. Opportunities of Sustainable Development of the Industry of Upholstered Furniture in Romania. A Case Study, Sustainability, Vol. 10, Issue 9, (SEP 2018), eISSN 2071-1050

[5] Barton-Pudlik, J. & Czaja, K. Fast-growing willow (Salix viminalis) as a filler in polyethylene composites, Composites Part B: Engineering. Vol. 143, (JUN 2018), pp. 68-74, ISSN 1359-8368, eISSN 1879-1069

[6] Niemczyk, M., Kaliszewski, A., Jewiarz, M., Wrobel, M. & Mudryk, K. Productivity and biomass characteristics of selected poplar (Populus spp.) cultivars under the climatic conditions of northern Poland. Biomass & Bioenergy, Vol. 111, (APR 2018), pp. 46–51, ISSN 0961-9534, eISSN 1873-2909

[7] Ichim, M., Filip, I., Stelea, L., Lisa, G. & Muresan, E. I. Recycling of Nonwoven Waste Resulting from the Manufacturing Process of Hemp Fiber-Reinforced Recycled Polypropylene Composites for Upholstered Furniture Products, Sustainability, Vol. 15, Issue 4, (FEB 2023), eISSN 2071-1050

[8] Branciforti, M. C., Marinelli, A. L., Marcio, K. & Nobre, A., 2009. Wood Polymer Composites Technology Supporting the Recovery and Protection of Tropical Forests: The Amazonian Phoenix Project, Sustainability, Vol. 1, Issue 4, (DEC 2009), pp. 1431-1443

[9] Renouard, N., Merotte, J., Kervoelen, A., Behlouli, K., Baley, C. & Bourmaud, A. Exploring two innovative recycling ways for poly-(propylene)-flax non wovens wastes, Polymer Degradation and Stability, Vol. 142, (AUG 2017), pp. 89–10, ISSN 0141-3910, eISSN 1873-2321

[10] Ciupan, C., Pop, E., Filip, I., Ciupan, E., Câmpean, E., Cionca, I. & Hereş, V. A new approach of the design process for replacing wooden parts of furniture, Proceedings of Modern Technologies in Manufacturing (MTEM 2017 - AMATUC), OCT 12-13, 2017, Cluj-Napoca, ISSN 2261-236X, ISBN 978-2-7598-9027-9, MATEC Web of Conferences, Art. No. 06002, E D P Sciences, F-91944 CEDEX A, FRANCE, DOI: 10.1051/matecconf/201713706002

[11] Ciupan, E., Lăzărescu, L., Filip, I., Ciupan, C., Câmpean, E., Cionca, I. & Pop, E. Characterization of a thermoforming composite material made from hemp fibers and polypropylene, Proceedings of Modern Technologies in Manufacturing (MTEM 2017 - AMATUC), OCT 12-13, 2017, Cluj-Napoca, ISSN 2261-236X, ISBN 978-2-7598-9027-9, MATEC Web of Conferences, Art. No. 08003, E D P Sciences, F-91944 CEDEX A, FRANCE, DOI: 10.1051/matecconf/201713708003

[12] Ciupan, C., Steopan, M., Pop, E., Campean, E., Filip, I. & Ciupan, E. Comparative analysis of different ribs used to rigidize the resistance structure of a sofa side made of composite materials based on vegetable fibers, Acta Technica Napocensis Series-Applied Mathematics, Mechanics and Engineering, Vol. 61, Issue I, (MAR 2018), pp. 39-44, ISSN 1221-5872

[13] Ciupan, E., Cionca, I., Ciupan, M. & Câmpean., E. The Optimization of Costs for the Thermoformed Frames from Natural Fiber Composites, Acta Technica Napocensis Series-Applied Mathematics, Mechanics and Engineering, Vol. 65, Issue 1, (FEB 2022), pp. 57-64, ISSN 1221-5872

[14] Ichim, M., Stelea, L., Filip, I., Lisa, G. & Muresan, E. I. Thermal and Mechanical Characterization of Coir Fibre–Reinforced Polypropylene Biocomposites, Crystals, Vol. 12, Issue 9, (SEP 2022), Art. No. 1249, eISSN 2073-4352

[15] Ezenwankwo, J., Zak, J. & Petrikova, I. (2022). Comparative Analysis of Polymeric Composite Reinforced with Glass Fibre and Viscose Rayon, Proceedings of the 33rd DAAAM International Symposium, pp.0496-0502, B. Katalinic (Ed.), Published by DAAAM International, ISBN 978-3-902734- 36-5, ISSN 1726-9679, Vienna, Austria, DOI: 10.2507/33rd.daaam.proceedings.069

[16] Cionca, I., Ciupan, E., Ciupan, M. & Ciupan, C. New Ecological Composite Materials for the Upholstered Furniture Industry, Acta Technica Napocensis Series-Applied Mathematics, Mechanics and Engineering, Vol. 66, Special Issue SI, (SEP 2023), ISSN 1221-5872, eISSN 2393-2988