



REMEDIES: Co-Creating a Plastic Litter Free Future

DELIVERABLE: D3.2

TITLE: Biodegradable fishing gear

This project is Co-funded by the European Union - HORIZON EUROPE program, under grant agreement No. 101093964. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the Climate Infrastructure and Environment Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.



REVISION TABLE		
Document Version	Date	Modified sections- Details
V.0.1	13.06.2025	Partial draft
V.1	25.07.2025	First Revision
V.2	28.07.2025	Final Revision

Contractual Date of Delivery	14.06.2025
Actual Date of Delivery	14.06.2025 for physical demonstrators 31.07.2025 for D3.2 document
Lead Contractor for this Deliverable	Cittadini spa (CIT)
Author(s)	Cesare Cittadini (CIT), Ilaria Canesi (NTT), Filip Miketa (BIOMI), Mariacristina Cocca - Roberta D'Auria (CNR)
Participant(s)	Cesare Cittadini (CIT), Filip Miketa (BIOMI), Ilaria Canesi - Daniele Spinelli (NTT), Mariacristina Cocca - Giuseppe De Lucia - Roberta D'Auria - Andrea Camedda (CNR), Leyre Hernandez (AITIIP), Sylvain Petit (SMILO), Dimitris Kokkinakis - Violetta Tsitsiliani (IHA)
WP contributing to the deliverable	WP3
Nature	Demonstrator
Version	V.2





Abbreviations

Acronym	Title
CDR	Cold Draw Ratio
CNW	Cellulose Nanowhiskers
DDR	Draw Down Ratio
HDPE	High Density Polyethylene
MFI	Melt Flow Index
MFR	Melt Flow Rate
PA	Polyamide
PBAT	Polybutylene Adipate Terephthalate
PBS	Polybutylene Succinate
PCL	Polycaprolactone
PES	Polyester
PHA	Polyhydroxyalkanoates
PHBV	Poly(3-hydroxybutyrate-co-3-hydroxyvalerate)
PHR	Parts per Hundred Rubber
PLA	Polylactic Acid
TDR	Total Draw Ratio
T _m	Melting Temperature
TPS	Thermoplastic Starch
TRL	Technology Readiness Level
WP	Work Package





Table of Contents

Executive Summary	7
I Introduction	13
1.1 Materials selection and target parameters	14
2. Blend production and viscosity characterization	15
2.1. Blend Production	15
2.2. Viscosity characterisation	17
2.3. Viscosity characterisation	19
3. Laboratory scale multifilament production: first phase	21
3.1 Spinning trials	21
3.1.1 Spinnability test compound 2. PBS/PBAT	23
3.1.2 Spinnability test compound 6. PBS/PBAT	24
3.1.3 Spinnability test compound 8. PLA/PBS	25
3.1.4 Spinnability test compound 9. PLA/PCL	26
3.1.5 Spinnability test compound 11. PBS/PHA	27
3.1.6 Spinnability test compound 12. Starch/PBAT:PHA	28
3.1.7 Spinnability test compound 13. Starch/PBAT	30
3.2 Mechanical characterization	31
3.2.1 Linear density	31
3.2.2 Tenacity and tensile properties	32
3.3 Discussion	34
3.4 Conclusions	36
4 Laboratory scale monofilament production: first phase	37
4.1 Spinning trials	37
4.1.1 Monofilament extrusion test compound 2. PBS/PBAT	39
4.1.2 Monofilament extrusion test compound 9. PLA/PCL	41
4.2 Mechanical characterization	42
4.2.1 Linear density	42
4.2.2 Tenacity and tensile properties	43
4.3 Discussion	43
4.4 Incorporation of Lignin as a Natural UV-Absorbing Additive	44
4.5 Conclusions	47





5	Blends for multifilament production: optimization phase	48
5.1	Preparation of blends	49
5.2	Rheological Characterization: Melt Flow Index and Viscosity Measurements	50
5.3	Preparation of Filler-Modified Blends	51
5.4	Conclusions	55
6	Laboratory scale multifilament production: second phase	56
6.1	Spinning trials	56
6.1.1	Spinnability test of Material A	57
6.1.2	Spinnability test of Material B	58
6.2	Mechanical characterization	60
6.2.1	Linear density	60
6.2.2	Tenacity and tensile properties	61
6.3	Result discussion	62
6.4	Conclusions	66
7	Blends for monofilament and multifilament production: optimization phase	67
8	Laboratory scale multifilament production: third phase	69
8.2	Mechanical characterization	71
8.2.1	Linear density, tenacity and tensile properties	71
8.3	Discussion	71
8.4	Conclusions	72
9	Laboratory scale monofilament production: second phase	74
9.1	Spinning trials	74
9.2	Mechanical characterization	76
9.3	Discussion	77
9.4	Conclusions	78
10	C 2.2 compound production for scale-up	82
11	Scale-up of monofilament production	85
11.1	Spinning phase	85
11.1.1	Starting conditions	86
11.1.2	CONDITION (SET) VI	87
11.1.3	CONDITION (SET) V 2-6	88
11.1.4	Spinning main difficulties	89
11.2	Linear density and mechanical characterization	90





11.3 Discussion	91
12 Production of fishing gears	92
12.1 Initial characterization tests	92
12.2 Production of monofilament fishing net.....	97
12.2.1 Yarn preparation.....	98
12.2.2 Weaving of the Net.....	99
12.2.3 Quality Control & Mending.....	105
12.2.4 Stretching and Heat Setting.....	106
12.2.5 Packaging.....	109
12.3 Production of monofilament braided rope	113
12.3.1 Twisting	113
12.3.2 Spool Winding	114
12.3.3 Braiding.....	115
12.3.4 Quality Control.....	117
12.3.5 Final Winding	119
13 Demo sites	120
13.1 Sinis Peninsula - Sardinia.....	120
13.1.2 Testing of biocompatible fishing nets in the Sinis Marine Protected Area.....	122
14 Conclusion and next steps.....	125
Annex I - Parameters related to the extrusion process	126



Executive Summary

This executive summary presents the key findings and outcomes of Deliverable D3.2 of Task 3.3 of Work Package 3 “Circular solutions for preventing plastic waste” of the REMEDIES project, focusing on the development and industrial production of biodegradable fishing gear using bio-based polymers.

Task 3.3 aims to reduce marine plastic pollution by replacing conventional fossil-based fishing gear with more sustainable alternatives made with bio-based biodegradable yarn.

To achieve the objectives of Task 3.3, a structured methodology with several steps was followed:

- ❖ **Material Development and Testing:** A variety of bio-based and biodegradable polymers were evaluated, including PLA, PBS, PBAT, PCL, PHBV, and starch-based blends. Additives such as talc, cellulose nanowhiskers (CNW), and lignin were incorporated to enhance UV stability and mechanical properties. Target properties included tenacity, elongation at break, melt flow index (MFI), and density.
- ❖ **Yarn Lab Scale Production and Optimization:** Multifilament and monofilament yarns were produced at laboratory scale. Compound 11 (PBS/PHA) and Compound 9 (PLA/PCL) showed the more promising results among the multifilament yarns, while Compound 2 (PBS/PBAT) demonstrated good performance for monofilament yarns. Optimization led to the selection of Compound C 2.2 (PBS/PBAT 85:15) for industrial scale-up of the monofilament yarn.
- ❖ **Industrial Scale-Up:** The scale-up process faced challenges such as high material waste and process instability. Despite these, a stable monofilament yarn was produced under Condition Set V2-6, achieving a tenacity of 2.42 cN/dtex and elongation of 87.2%. Approximately 50 kg of usable yarn was obtained from 300 kg of raw material.
- ❖ **Fishing Gear Production:** The monofilament yarn was used to produce a knotted fishing net and a braided rope. The net featured a 0.33 mm monofilament, 41.6 mm mesh size. The rope was realized with 12 carriers braided construction and has a 7 mm diameter. Mechanical tests confirmed acceptable performance, though still below that of nylon and HDPE in terms of tenacity.
- ❖ **Field Testing and Conclusions:** Field trials in Sardinia and in the Cyclades area, aim to assess the durability, degradation, and catch efficiency of the biodegradable fishing gears.

The C 2.2 compound (PBS/PBAT 85:15) demonstrated industrial feasibility and mechanical performance approaching HDPE monofilament. Further optimization is needed to enhance scalability and match the performance of fossil-based materials.



Index of Tables

Table 1 - Target parameters for Mono- and Multifilament yarn.....	14
Table 2 - Results of characterization during first round of trials.	15
Table 3 - Thermal data of the polymers used to realise blends.	17
Table 4 - Viscosity zero shear rate values for the different formulations.....	19
Table 5 - Compounds selected for first phase spinnability trials and their properties.....	21
Table 6 - Equipment’s parameters.	22
Table 7 - Compound 2. PBS/PBAT extrusion temperature profile.	23
Table 8 - Compound 2. PBS/PBAT spinning parameters of fibres.	23
Table 9 - Compound 6. PBS/PBAT extrusion temperature profile.	24
Table 10 - Compound 6. PBS/PBAT spinning parameters of fibres.....	25
Table 11 - Compound 8. PLA/PBS extrusion temperature profile.	26
Table 12 - Compound 9. PLA/PCL extrusion temperature profile.	26
Table 13 - Compound 9. PLA/PCL spinning parameters of fibres.	26
Table 14 - Compound 11. PBS/PHA extrusion temperature profile.....	27
Table 15 - Compound 11. PBS/PHA spinning parameters of fibres.....	28
Table 16 - Compound 12. Starch/PBAT:PHA extrusion temperature profile.	29
Table 17 - Compound 12. Starch/PBAT:PHA spinning parameters of fibres.	29
Table 18 - Compound 13. Starch/PBAT extrusion temperature profile.....	30
Table 19 - Compound 13. Starch/PBAT spinning parameters of fibres.....	31
Table 20 - Linear density values.	31
Table 21 - Mechanical characterization results.....	33
Table 22 - Results of characterization during third round of trials	37
Table 23 - Compounds selected for spinnability trials and their properties.....	38
Table 24 - Extrusion temperature profile for compound 2. PBS/PBAT	40
Table 25 - Drawing parameters for the filaments obtained with compound 2. PBS/PBAT	40
Table 26 - Extrusion temperature profile for compound 9. PLA/PCL.....	41
Table 27 - Drawing parameters for the filaments obtained with compound 9. PLA/PCL	41
Table 28 - Linear density values.	42
Table 29 - Mechanical characterization results.....	43
Table 30 - PBS/PBAT blends with different amount of lignin.....	45
Table 31 - MFI results for the different blends.....	46
Table 32 - Viscosity zero shear rate values for the different formulations	46
Table 33 - PLA/PCL blends.....	48
Table 34 - MFI results for the different blends.	50
Table 35 - Viscosity results for the different blends.....	50
Table 36 - PLA/PCL blend with filler.....	51
Table 37 - Characterization data of the compounds of PLA:PCL blends.....	53
Table 38 - MFI and Viscosity results for the different materials.....	54
Table 39 - Compounds selected for second phase spinnability trials and their properties.....	56
Table 40 - Material A extrusion temperature profile.....	57
Table 41 - Material A spinning parameters of filaments.	57
Table 42 - Material B extrusion temperature profile.	59





Table 43 - Material B spinning parameters of B_Filament I	60
Table 44 - Data of A_Filament	61
Table 45 - Mechanical characterization results.....	61
Table 46 - Melt spinning trial overview	62
Table 47 - Results of characterization of fifth group of trials.....	67
Table 48 - Material C selected for the third phase spinnability trial and its properties.	69
Table 49 - Material C temperature profile and spinning parameters of filaments.	70
Table 50 - Linear density and mechanical tensile properties of filaments obtained from material C.	71
Table 51 - Compounds selected for spinnability trials and their properties.....	74
Table 52 - Extrusion temperature profile of filaments obtained from the three compounds.	75
Table 53 - Drawing parameters filaments obtained from the three compounds.....	75
Table 54 - Mechanical characterization results and linear density values.....	77
Table 55 - Test comparison between NTT and CIT data.....	79
Table 56 - Results of characterization of first scaling up trials.....	83
Table 57 - Starting processing parameters.	86
Table 58 - Processing parameters of CONDITION (SET) VI: upstream zones.....	87
Table 59 - Processing parameters of CONDITION (SET) VI: downstream zones.....	87
Table 60 - Processing parameters of CONDITION (SET) V 2-6: upstream zones.....	88
Table 61 - Processing parameters of CONDITION (SET) V 2-6: downstream zones.....	88
Table 62 - Linear density values and tensile properties of bobbins under the two processing conditions.	90
Table 63 - Linear density values and tensile properties of Condition (Set) V2-6 monofilaments	91
Table 64 - Test results at CIT LAB from random spools of different sets:.....	94
Table 65 - Comparison of Remedies yarn vs Fossil based monofilament	95
Table 66 - Thermal treatment tests of the Remedies monofilament Condition Set V2-6.....	96
Table 67 - Definition of the fishing net demonstrator	97
Table 68 - Results of the mechanical tests on the Bio-degradable net.....	112
Table 69 - Mechanical characterization of the braid.....	118



List of Figures

All Figures in this document have been created by Remedies Partners unless otherwise stated in the figure caption

Figure 1 - Co-rotating twin screw extrusion line in Bio-Mi facility.....	15
Figure 2 - Samples of blends ready for shipment to NTT for further analysis and processing trials.....	16
Figure 3 - Rotational rheometer Thermo Scientific Haake RheoStress 6000.....	18
Figure 4 - Viscosity characterisation of the different formulations.....	18
Figure 5 - Viscosity characterisation of the different formulations.....	20
Figure 6 - Melt spinning Hills TRC Equipment (left) and spinnhead with 36 filament (right).	22
Figure 7 - Example of multifilament bobbin of "2" Fibre 1	24
Figure 8 - Samples obtained from compound 6. PBS/PBAT: "6" Fibre 1 (left) and "6" Fibre 2 (right).....	25
Figure 9 - Example of multifilament bobbin of "9" Fibre 5.	27
Figure 10 - Example of multifilament bobbin of "11" Fibre 4.....	28
Figure 11 - Multifilaments obtained from compound 12. Starch/PBAT:PHA	29
Figure 12 - Representation of the degradation for compound 12. Starch/PBAT:PHA.	30
Figure 13 - Multifilaments obtained from compound 13. Starch/PBAT	31
Figure 14 - Shimadzu universal mechanical test machine.	33
Figure 15 - Comparison of all the multifilaments obtained under stable processes.....	35
Figure 16 - Comparison of elongation at break values between all the multifilaments	35
Figure 17 - DSC thermograms of Remedies 2 (left) and Remedies 9 (right) compounds 1st heating.....	38
Figure 18 - Samples of materials shipped to NTT.....	38
Figure 19 - Monofilament extrusion line scheme.....	39
Figure 20 - Compound PBS/PBAT: "2" Filament 1 (left) and "2" Filament 2 (right).	40
Figure 21 - Filaments obtained from compound 9. PLA/PCL.....	42
Figure 22 - Comparison between all the monofilaments of compounds 2. PBS/PBAT and 9. PLA/PCL.....	44
Figure 23 - Ceast Melt Flow Junior 6943 melt flow index tester.....	45
Figure 24 - Samples of materials shipped to CNR for further optimization.....	48
Figure 25 - Thermo HAAKE MiniLab twin screw extruder.	49
Figure 26 - Viscosity graphic of different composition of PLA/PCL.....	51
Figure 27 - Compounding of PLA:PCL with addition of cellulose fibres	52
Figure 28 - PLA:PCL compounds with addition of talc (left) and with addition of cellulose fibres (right).....	52
Figure 29 - Samples of PLA:PCL compounds with addition of talc and CNW	53
Figure 30 - Viscosity graphic of different materials.....	55
Figure 31 - Spinned bobbins of various A_Filament_x	58
Figure 32 - Spinning trials: various conditions.....	59
Figure 33 - B_Filament 1 obtained from Material B.	60
Figure 34 - Comparison of force at break and tenacity values of all the filaments from Material A.....	63
Figure 35 - Optical microscopy of Material A filaments – longitudinal images.	64
Figure 36 - Optical images of B_Filament	65
Figure 37 - Optical microscopy of Material B waste – longitudinal images.	65
Figure 38 - Comparison of all the filaments obtained from Material A and from compound 9. PLA/PCL obtained during the first phase of multifilament melt spinning trials.....	66



Figure 39 - Samples of obtained granulates	68
Figure 40 - Obtained materials shipped to NTT for final validation.....	68
Figure 41 - Filaments obtained from Material C.....	70
Figure 42 - Comparison of force at break and tenacity values of all the filaments from Material C.....	72
Figure 43 - Comparison of the filaments from Material C and the compound I I. PBS/PHA	73
Figure 44 - Steps for extrusion parameter optimization to achieve stable processing conditions.	75
Figure 45 - Filaments obtained from compounds C 2.1, C 2.2, C2.3.....	76
Figure 46 - Comparison between all the monofilaments obtained from compounds C 2.1, C 2.2, C2.3.....	78
Figure 47 - Comparison between monofilaments from compounds C 2.1, C 2.2, C2.3 and PBS/PBAT.....	79
Figure 48 - Diagram Force – Elongation of Sample 2.2_03	81
Figure 49 - Compounding during scaling up trial.....	82
Figure 50 - Processing and control parameters during compounding step	82
Figure 51 - Thermal characterization of raw materials PBS (left) and PBAT (right) 1st heating curve.....	83
Figure 52 - Thermal characterization of PBS:PBAT compound, 1st heating curve	83
Figure 53 - The pallet with 300kg of compounds shipped to NTT	84
Figure 54 - The 300 kg pallet of Compound C 2.2 in NTT’s laboratory.	85
Figure 55 - Monofilament industrial equipment: different zones.....	86
Figure 56 - Examples of collected spools.....	88
Figure 57 - Difficulties and optimization during processing and waste produced	89
Figure 58 - The Dynamometer used to test the monofilament yarn	92
Figure 59 - Test of the linear density	93
Figure 60 - Test of diameter of the monofilament.....	93
Figure 61 - Diagram Force – Elongation of sample of condition VI	93
Figure 62 - Diagram Force – Elongation of sample of condition V2-6.....	94
Figure 63 This in an example of 3 meshes of a double knot monofilament nylon net.....	97
Figure 64 - Monofilament fishing net production steps	98
Figure 65 - SSM Xeno Electronic Winding machine	98
Figure 66 - The creel loaded with the 200 DIN bobbins	99
Figure 67 - Type of knot.....	99
Figure 68 - General scheme of a knotted fishing net machine	100
Figure 69 - CIT Fishing Net Loom.....	101
Figure 70 - The manual spool winder used to fill the spools	102
Figure 71 - Particular of the loom’s carrier where are loaded the spools.....	102
Figure 72 - Some of the mechanical cams responsible for all the synchronized movements of the loom....	103
Figure 73 - Needlebed with the “dust” on the knitting elements.....	104
Figure 74 - The net produced by the loom is collected on a roll	104
Figure 75 - Two operators inspect each part of the opened net.....	105
Figure 76 - One of the special ends where the iron combs are fixed	106
Figure 77 - The net loaded on the 25mt carrier of the heat setting machine.....	107
Figure 78 - A view of the 2 nets stretched on the carrier	108
Figure 79 - The net stretched is measured to reach the correct mesh size	108
Figure 80 - The opening of the vacuum autoclave after steam heat setting treatment	109
Figure 81 - The operators are packing the 4 nets in one small bale	110





Figure 82 - The final appearance of a bale of knotted bio-degradable monofilament net.....	111
Figure 83 - Front view of the bale of net	111
Figure 84 - Particular view of the test for determining the mesh breaking load.....	112
Figure 85 - Braid production steps	113
Figure 86 - Take-up of the one head twisting machine.....	113
Figure 87 - Spool winder	114
Figure 88 - Operating diagram of a braiding machine	115
Figure 89 - Carrier components	115
Figure 90 - Braiding machine with a detail view of the 12 rotating carriers.....	116
Figure 91 - Testing of the breaking load of the braid.....	117
Figure 92 - Stress - Strain diagram of the braid tested	118
Figure 93 - The aspect of the braided rope made of bio-degradable monofilament.....	119
Figure 94 - The final aspect of the bobbin of braided rope for Remedies project.....	119
Figure 95 - Sardinia demo site - Sinis Peninsula.....	121
Figure 96 - Image of the coast of Sinis Peninsula	121
Figure 97 - Image of a shore in Sardinia demo site.....	122
Figure 98 - Images of a fisherman and its fishing net.....	123
Figure 99 - A typical knotted fishing net with its braided rope	124





I Introduction

Task 3.3 of the REMEDIES project focuses on the development and industrial production of biodegradable fishing gear using bio-based biodegradable polymers. The aim was to produce at least 1000m of biodegradable fishing gears (>700m of fishing nets and >300m of ropes) reaching TRL 7.

The main objective of this task is to identify, formulate, and optimize polymer blends suitable for the production of mono- and multifilament yarns, which can be used in the manufacturing of the fishing nets and ropes as system prototype demonstrators in operational environment.

The present Deliverable D3.2 documents the progress and outcomes of this task, highlighting the technical feasibility and performance of the developed materials in real-world applications.

To achieve the objectives of Task 3.3, a structured methodology was followed. Initially, suitable bio-based and biodegradable polymers were selected based on their mechanical and rheological properties. These polymers were compounded into various blends and characterized for viscosity, melt flow index, and mechanical performance. Laboratory-scale trials were conducted to produce multifilament and monofilament yarns, followed by mechanical testing and optimization of the masterbatch blends. Promising formulations were scaled up for industrial production, and the resulting yarns were used to fabricate fishing nets and braided ropes. Field tests will be then conducted to evaluate the durability and performance of the biodegradable gear in marine environments.

Deliverable D3.2 is structured as follows:

- Chapter 1: Introduction – Provides an overview of the task objectives and context and the selection of the polymers made.
- Chapter 2: Blend Production and Viscosity Characterization – Describes the formulation and rheological analysis of polymer blends.
- Chapter 3: Laboratory Scale Multifilament Production – Details the initial spinning trials and mechanical characterization of multifilament yarn.
- Chapter 4: Laboratory Scale Monofilament Production – Covers the extrusion trials and performance evaluation of monofilaments.
- Chapter 5: Optimization Phase – Discusses the refinement of blends and incorporation of additives.
- Chapter 6: Second Phase of Multifilament Production – Presents further trials and mechanical testing.
- Chapter 7: Optimization for Monofilament and Multifilament – Summarizes the final blend selection.
- Chapter 8: Third Phase of Multifilament Production – Reports on the performance of optimized blends.
- Chapter 9: Second Phase of Monofilament Production – Evaluates the final monofilament trials.
- Chapter 10: Scale-up of Compound Production – Describes the industrial-scale compounding process.
- Chapter 11: Scale-up of Monofilament Production – Details the industrial spinning and challenges encountered.
- Chapter 12: Production of Fishing Gears – Explains the manufacturing of nets and ropes.
- Chapter 13: Demo Sites – Outlines the field testing and deployment of the biodegradable gear.
- Chapter 14: Conclusion and next steps



I.1 Materials selection and target parameters

Task 3.3 partners CIT, NTT, BIO-MI, CNR, AITIIP, first discussed about the choice of the best polymers to be used in formulations for mono- and multifilament yarn production for fishing nets and gears. The discussion concerned the opportunity to use biobased but not biodegradable polymers (bio-PA, bio-PE) or bio-based and biodegradable polymers as required in the project. The high commercial cost or availability of some polymers led to the exclusion of some such as PHA or PCL: common opinion looked for a compromise between biobased and biodegradable polymers with good mechanical properties but not too expensive.

Based on their own experience and data from scientific literature NTT suggested two of the most important key parameters to be considered to formulate blends suitable for yarn production: MFI (target range of 10-15 g/10min) and polymer density (target range 1.2 - 1.35 g/cm³). CIT provided mechanical target values for the most common used fossil based mono- and multifilament yarn, as show below in **Table I**. Tenacity target value for monofilament was around 4.2 - 5 cN/dtex and for multifilament 8 cN/dtex, average tensile strain at break target value was indicated in a range of 18-24% for both applications.

To develop spinning suitable compounds, NTT suggested to use PBS and PBAT polymers (spinning or filming grade), formulating a mixture with PBS matrix containing from 0% PBAT up to 50% as the first choice; PLA polymer (spinning or filming grade) could also be added in percentage from 10 to 20% depending on the required mechanical characteristics of the blend.

Table I reports the summary of the selected materials and target parameters to be considered for the formulations.

Table I - Target parameters for Mono- and Multifilament yarn.

	Fishing nets		Fishing gears	
Fossil-based material	HDPE, PA		HDPE, PA, PES	
Bio-based polymers	PLA/PBS, PHBV/PBS, PLA/PHB, PBS/PBAT, PBS			
Natural fillers	CaCO ₃ , nanocellulose, talc			
Key properties of fossil-based yarn	Monofilament		Multifilaments	
	<i>Tenacity</i>	4.2 – 5 cN/dtex	<i>Tenacity</i>	8.1 cN/dtex
	<i>Tensile strain at break</i>	18 – 24 %	<i>Tensile strain at break</i>	19.5 %

2. Blend production and viscosity characterization

2.1. Blend Production

As it was already mentioned, it was agreed between partners that for first trials Bio-Mi will prepare 13 different blends based on PBS, PBAT, PLA, PCL, PHBV and TPS.



Figure 1 - Co-rotating twin screw extrusion line in Bio-Mi facility

During preparation of blends Bio-Mi followed methodology and internal protocols related with characterization of raw materials, drying of raw materials, blending via twin screw extrusion, characterization of blends (rheology, physical, thermal properties), drying of blends and finally packing materials into aluminium bags. The results of the characterization are shown in **Table 2** below.

Table 2 - Results of characterization during first round of trials.

Material	$T_m, ^\circ\text{C}$	MFR, g/10 min 190 °C, 2.16 kg	Density, g/cm ³	Moisture, %
1. PBS	115.2	5.4	1.2	0.3
2. PBS:PBAT	116.3	5.0	1.2	0.4
3. PBS:PBAT	114.8	5.7	1.2	0.4
4. PBS:PBAT	114.6	6.7	1.3	0.5
5. PBS:PBAT	115.6	6.5	1.2	0.4



6. PBS:PBAT	116.9	6.7	1.3	0.4
7. PLA:PBS	110.2 / 146.3	3.7	1.2	0.2
8. PLA:PBS	112.9 / 144.9	3.6	1.2	0.2
9. PLA:PCL	60.4 / 147.4	7.8	1.2	0.3
10. PBAT:PHA	118.8 / 168.1	8.5	1.2	0.4
11. PBS:PHA	115.4 / 168.4	9.6	1.2	0.3
12. Starch/PBAT:PHA	123.2 / 167.2	8.8	1.2	0.5
13. Starch/PBAT	117.5	4.7	1.3	0.5



Figure 2 - Samples of blends ready for shipment to NTT for further analysis and processing trials

First trials related with development phase at TRL5 passed smoothly except formulation no.10 where Bio-Mi team experienced pelletizing issues. Formulations were based on commercially available bio-polyesters such as PHAs, PBS, PLA, PBS, PCL and TPS. Materials were shipped to NTT for further investigation and characterization. As it was agreed between partners, next testing trials will be related only with formulations which will show best results.



2.2. Viscosity characterisation

In order to evaluate their viscosity profile CNR performed Rheological tests on three blends prepared and supplied by BIOMI (Material Remedies 7-8-9):

7. PLA/PBS
8. PLA/PBS
9. PLA/PCL

Prior to testing, a literature review was conducted to determine the appropriate testing temperature, because the blends are composed of polymers with differing melting temperatures. These polymers exhibit distinct thermal behaviours, and selecting a common testing temperature requires identifying a condition that ensures complete melting of all components without inducing degradation. In **Table 3** the melting temperature and degradation temperature of PLA, PBS, PCL are reported,

Table 3 - Thermal data of the polymers used to realise blends.

Sample ID	Melting Temperature (°C)	Degradation Temperature (°C)
PLA	150-170°C	370°C
PBS	110-116°C	396°C
PCL	60-80°C	360-420°C

Based on the literature data, a temperature of 200°C was selected for performing rheological tests on all the blends. This temperature ensures full melting of PLA, PCL, and PBS, allowing for meaningful comparison of their flow behaviour under identical conditions. Viscosity measurements were then conducted using the rotational rheometer (Thermo Scientific Haake RheoStress 6000), reported in **Figure 3**, with parallel plate geometry (25 mm diameter, 1 mm gap), under controlled temperature and shear conditions, as previously described. The shear rate was varied from 0.5 s⁻¹ to 300 s⁻¹, and the resulting viscosity values were recorded for each sample.



Figure 3 - Rotational rheometer Thermo Scientific Haake RheoStress 6000.

Data analysis was carried out by extracting viscosity values at different shear rates using the rheometer's software. The obtained data were processed in Microsoft Excel, where the logarithm of viscosity [Pa*s] was plotted against the logarithm of shear rate [s⁻¹], (**Figure 4**). From the resulting curves, the zero-shear viscosity values were identified and reported in **Table 4**.

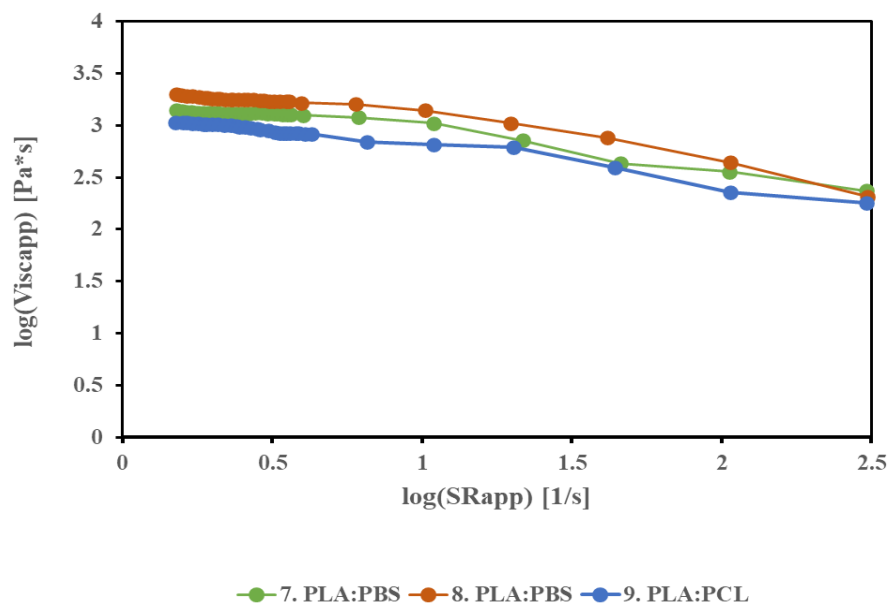


Figure 4 - Viscosity characterisation of the different formulations

Table 4 - Viscosity zero shear rate values for the different formulations.

Sample ID	Blend composition	Viscosity ZEROSHEAR (Pa*s)
7	PLA/PBS	2058 ±141
8	PLA/PBS	2861 ±277
9	PLA/PCL	1737 ±309

All samples exhibit a typical polymer behaviour characterised by a decrease in viscosity with increasing shear rate. This behaviour is favourable for melt processing techniques such as spinning.

- Sample ID 7 (PLA/PBS): this blend displays an intermediate viscosity profile across the entire shear rate range. The viscosity remains relatively stable at low shear rates and decreases progressively as the shear rate increases; this indicates a good processability.
- Sample ID 8 (PLA/PBS): this formulation shows the highest viscosity values throughout the shear rate range, particularly in the low-to-intermediate shear region, this suggests a higher resistance to flow.
- Sample ID 9 (PLA/PCL): this blend consistently exhibits the lowest viscosity values, indicating greater melt fluidity. The curve shows a more pronounced shear-thinning effect at lower shear rates, suggesting a less entangled polymer network.

Sample ID 7 presents a balanced rheological profile, positioning it as a compromise between processability and melt strength, and thus a promising candidate for multifilament spinning.

2.3. Viscosity characterisation

As part of the characterisation screening, viscosity versus shear rate was measured for all the candidate formulations.

Figure 5 shows the logarithm of viscosity (Viscap in Pa*s) versus the logarithm of shear rate (SRap in 1/s) results for various formulations. In general, viscosity decreases with increasing shear rate in all cases, a characteristic of shear-thinning behaviour (pseudoplasticity), typical for polymer melts.

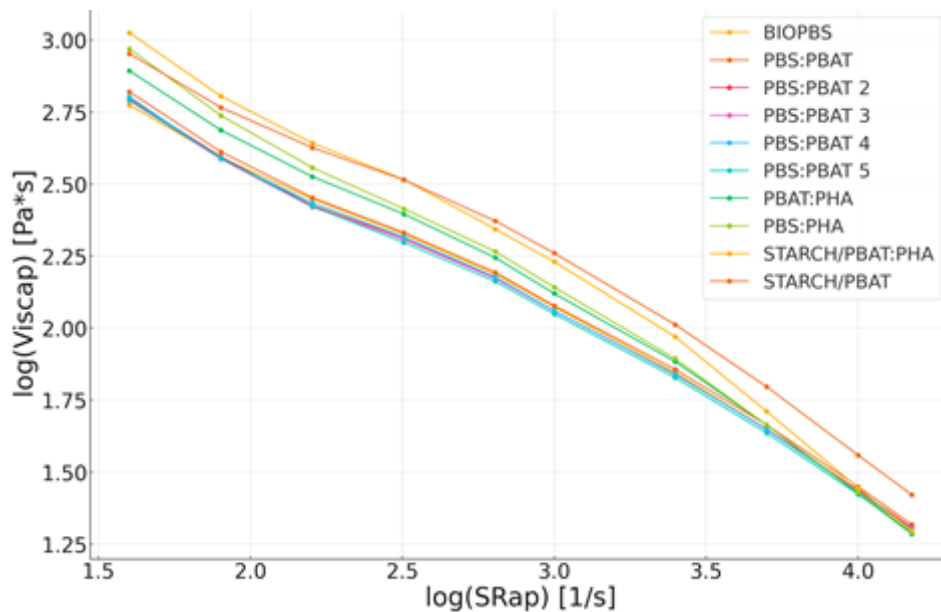


Figure 5 - Viscosity characterisation of the different formulations

BIOPBS shows a moderate shear thinning, with a near-linear decline in log-log space. PBS:PBAT blends show similar trends, with some variation in absolute viscosity. Blends 2-4 have slightly higher viscosities at most shear rates compared to blend 5. PBAT:PHA is more viscous across all shear rates, likely due to higher molecular weight or stronger intermolecular interactions. PBS:PHA has the highest viscosity overall among PBS- or PBAT-based blends and has slightly steeper shear thinning compared to PBAT:PHA. STARCH/PBAT:PHA has extremely high initial viscosity; due to complex polysaccharide structure and likely interfacial interactions. STARCH/PBAT has as well high viscosity. It shows strong shear thinning, but retains more viscosity than others at high shear, possibly indicating poor flowability or strong matrix-filler interactions.

In conclusion, all materials exhibit pseudoplastic (shear-thinning) behaviour. Starch-containing blends have the highest viscosity at low shear rates — potentially problematic for flow but beneficial for structural rigidity. PBS:PBAT blends are relatively balanced, showing good flowability and moderate shear thinning. PHA-containing blends increase melt viscosity significantly, possibly due to higher crystallinity or entanglement density. PBS:PHA and PBAT:PHA offer a balance between flowability and structural integrity. For easier processing, BIOPBS or PBS:PBAT blends would be more suitable.



3. Laboratory scale multifilament production: first phase

3.1 Spinning trials

Considering material characterization performed by BIOMI (MFR, density) and viscosity data by AITIIP and CNR, NTT selected the most promising compounds to be processed by melt spinning (on a lab scale equipment) to produce multifilament yarns, the most challenging process. **Table 5** presents the selected compounds with the respective melting point (T_m) and the melt flow rate value (MFR).

BIOMI provided NTT with 2-3 kg of each selected compound.

Table 5 - Compounds selected for first phase spinnability trials and their properties

Compound	T_m (°C)	MFR (g/10 min) [190 °C, 2.16 kg]
2. PBS/PBAT	116.3	5.0
6. PBS/PBAT	116.9	6.7
8. PLA/PBS	112.9 / 144.9	3.6
9. PLA/PCL	60.4 / 147.4	7.8
11. PBS/PHA	115.4 / 168.4	9.6
12. Starch/PBAT:PHA	123.2 / 167.2	8.8
13. Starch/PBAT	117.5	4.7

The moisture content was measured after the drying of each material and before processing, in a Radwag MA 50/1.X2.A. WH equipment, which has the sensibility to measure up to 1 part per million (PPM). The moisture content was registered for all the blends in a range of 0.2-0.5%.

The spinnability tests were carried out on a lab-scale equipment. **Table 6** shows the equipment specifications, mainly regarding temperatures, throughputs and speeds. **Figure 6** shows a representative scheme and characteristics of the equipment used for the trials (a Melt spinning Hills TRC Equipment), where the main parameters are:

- V_0 : Melt Pump Throughput Speed (g/min);
- V_1 : Feed Roll Speed (m/min);
- V_2 : Draw Roll Speed (m/min);
- V_3 : Relax Roll Speed (m/min);

- *DDR*: Draw Dawn Ratio ($V1/V0$), referred also as “hot stretching”;
- *CDR*: Cold Draw Ratio ($V2/V1$), referred also as “cold stretching” or “drawing ratio”.

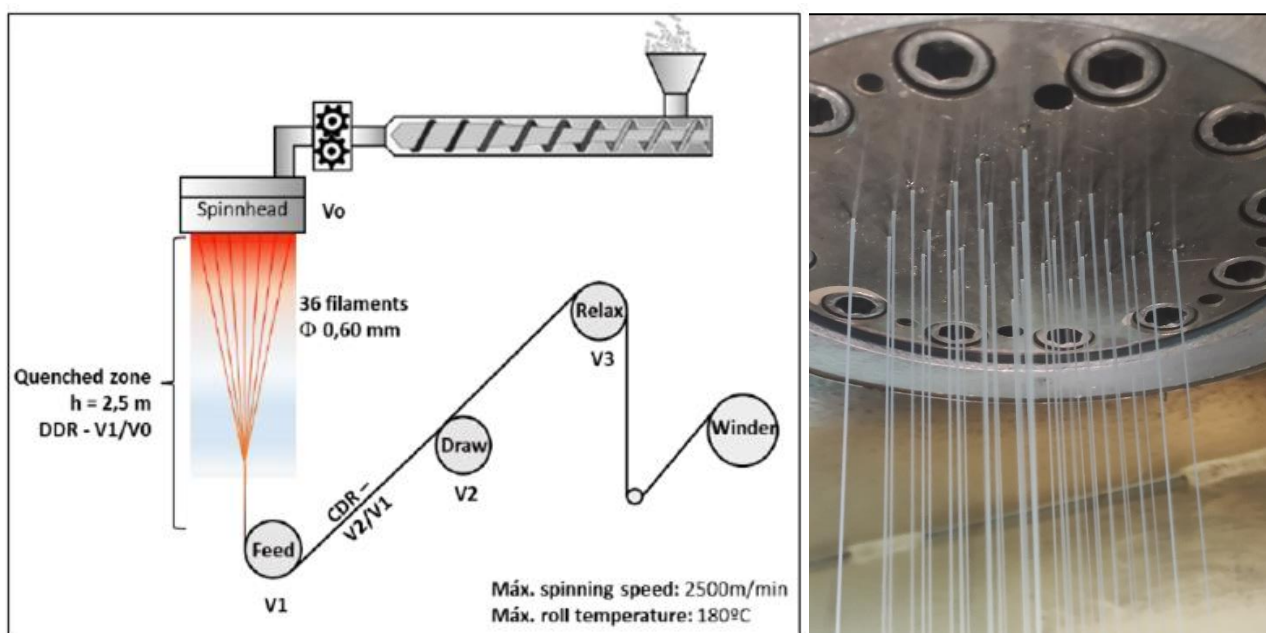


Figure 6 - Melt spinning Hills TRC Equipment (left) and spinnhead with 36 filament (right).

Table 6 - Equipment's parameters.

Parameter	Minimum	Maximum
Melt pump speed (rpm)	6	48
Melt pump capacity (cm ³ /rotation)	0.6	
Godet (roll) speeds (m/min)	100*	2500
Melt pump/spinneret pressure (bar)	0	250

* This speed can be lower but without any heating applied to the godet.

The spinning trials were performed using a 36-capillary spinneret, with a diameter of 0.6 mm (L/D=4) in each capillary. The materials were dried before the tests at 65°C/14h. A spin finish oil adequate for polyester fibres was used.

Each material was tested according to the following steps:

- Spinning temperatures: the temperatures were adjusted to achieve an optimal process stability;
- Throughput: the maximum possible throughput without defects such as overflow, shark skin, melt fracture, over-pressure or screw effort was experimentally determined;
- Take-up and draw speed: the value was adjusted to achieve the maximum and minimum stable conditions;

- **Samples:** if a stable process was achievable, it was intended to obtain 3 different samples (bobbins), with a length of at least 200 meters. Due to the low quantity of material and the need to find the optimal processing conditions, for all the stable processes, at least two samples of fibres were produced:
 - Sample 1 (*DDR-*, *CDR+*): in this type of fibre, the minimum hot stretching (*DDR-*) is applied, followed by the maximum cold stretching (*CDR+*). In these conditions, it's expected to achieve the highest tenacity for each material.
 - Sample 2 (*DDR+*, *CDR+*): in this type of fibre, the maximum hot stretching (*DDR+*) is applied, followed by the maximum cold stretching (*CDR+*). In these conditions, it's expected to achieve the minimum linear densities for each material.

3.1.1 Spinnability test compound 2. PBS/PBAT

The first tested compound was 2. PBS/PBAT. At the temperature of 120 °C, the material showed a moisture content of zero.

Spinning trials led to the production of three fiber typologies, applying different stretches and one defined temperature profile T1. The following tables (**Table 7** and **Table 8**) provide the extrusion parameters set for the trials. Fibre 2 was obtained under an unstable spinning process that may lack filaments and possess other defects.

Other parameters used in the production of these fibres are detailed in “Annex 1 - parameters related to the extrusion process”. **Figure 7** shows a bobbin of “2” Fibre 2 multifilament.

Due to the high viscosity and lower MFR observed in processing, it was concluded that compound 2 has low affinity with multifilament melt spinning process.

Table 7 - Compound 2. PBS/PBAT extrusion temperature profile.

Temperature profile	Fibre reference	Extruder heating zones (°C)			Melt pump (°C)	Melt temperature (°C)	Transfer line (°C)	Spinneret (°C)	Speed (rpm)	Pressure (bar)
		1	2	3						
2. PBS/PBAT T1	“2” Fibre 1 “2” Fibre 2 “2” Fibre 3	150	165	180	185	180	160	185	30	47-51

Table 8 - Compound 2. PBS/PBAT spinning parameters of fibres.

Fibre reference	Throughput (g/min)	Rolls speed (m/min)			Rolls temperature (°C)			DDR (V1/V0)	CDR (V2/V1)
		R1	R2	R3	R1	R2	R3		
“2” Fibre 1	21.28	100	210	189	45	36	29	57	2.10
“2” Fibre 2*	21.28	125	225	200	45	36	29	72	1.80
“2” Fibre 3	21.28	120	225	200	45	35	29	69	1.88

* Fibres obtained under an unstable spinning process that may lack filaments and possess other defects.



Figure 7 - Example of multifilament bobbin of "2" Fibre 1

3.1.2 Spinnability test compound 6. PBS/PBAT

Compound 6. PBS/PBAT at the temperature of 120 °C, showed a moisture content of zero.

Spinning trials were carried out testing three different temperature profiles as listed in **Table 9**.

Temperature profile T1 didn't allow the collection of the filaments, since the material showed a low melt elongation, while at T3 the compound was not spinnable. At temperature profile T2, it was possible to obtain and collect filaments, "6" Fibre 1 and "6" Fibre 2, but with a very high linear density and within an unstable process (**Table 10**). Other parameters used in the production of these fibres are detailed in "**Annex I** - parameters related to the extrusion process".

Table 9 - Compound 6. PBS/PBAT extrusion temperature profile.

Temperature profile	Fibre reference	Extruder heating zones (°C)			Melt pump (°C)	Melt temperature (°C)	Transfer line (°C)	Spinnere t (°C)	Speed (rpm)	Pressure (bar)
		1	2	3						
6. PBS/PBAT T1	Not spinnable	163	195	199	225	217	221	228	30	-
6. PBS/PBAT T2	"6" Fibre 1 "6" Fibre 2	163	195	199	225	217	231	245	30	43
6. PBS/PBAT T3	Not spinnable	175	200	210	230	225	235	260	30	6

Table 10 - Compound 6. PBS/PBAT spinning parameters of fibres.

Fibre reference	Throughput (g/min)	Rolls speed (m/min)			Rolls temperature (°C)			DDR (V1/V0)	CDR (V2/V1)
		R1	R2	R3	R1	R2	R3		
"6" Fibre 1*	23.06	29.9	33.9	35.7	45.8	33.3	29.4	17.18	1.13
"6" Fibre 2*	23.06	29.9	33.9	35.7	45.8	33.3	29.4	17.18	1.13

* Fibres obtained under an unstable spinning process that may lack filaments and possess other defects.

Figure 8 shows samples of the fibers obtained from compound 6. PBS/PBAT. The fibers ultimately detached from the spool due to their high linear density and the instability of the process used to produce them. This material exhibited an extremely low flow rate, resulting from the low spinning speeds, making it unsuitable for this multifilament melt spinning process. Alternative extrusion methods, such as monofilament extrusion, may be more suitable for this material.

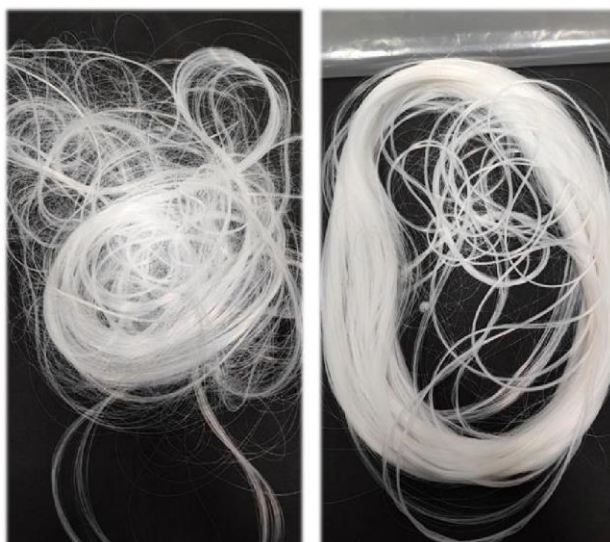


Figure 8 - Samples obtained from compound 6. PBS/PBAT: "6" Fibre 1 (left) and "6" Fibre 2 (right).

3.1.3 Spinnability test compound 8. PLA/PBS

Compound 8. PLA/PBS at the temperature of 120 °C, showed a moisture content of zero. Spinning trials were carried out testing two temperature profiles as detailed in **Table 11**. Under the temperature profile T1, the material exhibited extremely high viscosity, preventing it from being stretched in the quenched zone. When the temperatures were increased to profile T2, the material began to drip. This behaviour suggests that the applied temperatures are excessively high for at least one of the polymers in the formulation, likely the PBS component. Based on these findings, it is concluded that compound 8 (PLA-PBS) is not suitable for the melt spinning process.



Table 11 - Compound 8. PLA/PBS extrusion temperature profile.

Temperature profile	Fibre reference	Extruder heating zones (°C)			Melt pump (°C)	Melt temperature (°C)	Transfer line (°C)	Spinneret (°C)	Speed (rpm)	Pressure (bar)
		1	2	3						
8. PLA/PBS T1	Not spinnable	175	201	218	230	225	210	220	30	84
8. PLA/PBS T2	Not spinnable	175	201	218	240	230	235	240	30	8

3.1.4 Spinnability test compound 9. PLA/PCL

Compound 9. PLA/PCL at the temperature of 120 °C, showed a moisture content of zero. Using the temperature profile T1, as presented in **Table 12**, it was possible to collect five different filaments tuning spinning parameters (**Table 13**). Although Fibres 1 and 3 were obtained under unstable processes, this material presented a suitable flow rate and stability under the melt-spinning process. Other parameters used in the production of these fibres are detailed in “Annex I - parameters related to the extrusion process”.

Figure 9 shows a bobbin of “9” Fibre 5 multifilament.

Table 12 - Compound 9. PLA/PCL extrusion temperature profile.

Temperature profile	Fibre reference	Extruder heating zones (°C)			Melt pump (°C)	Melt temperature (°C)	Transfer line (°C)	Spinneret (°C)	Speed (rpm)	Pressure (bar)
		1	2	3						
9. PLA/PCL T1	“9” Fibre 1 “9” Fibre 2 “9” Fibre 3 “9” Fibre 4 “9” Fibre 5	175	200	215	230	225	210	210	30	21-25

Table 13 - Compound 9. PLA/PCL spinning parameters of fibres.

Fibre reference	Throughput (g/min)	Rolls speed (m/min)			Rolls temperature (°C)			DDR (V1/V0)	CDR (V2/V1)
		R1	R2	R3	R1	R2	R3		
“9” Fibre 1*	21.28	100	115	114	45	35	30	57	1.15
“9” Fibre 2	21.28	100	110	109	45	36	29	57	1.10
“9” Fibre 3*	21.28	625	720	713	47	35	29	358	1.15
“9” Fibre 4	21.28	615	715	704	44	35	29	353	1.16
“9” Fibre 5	21.28	615	615	615	44	35	30	353	1.00

* Fibres obtained under an unstable spinning process that may lack filaments and possess other defects.





Figure 9 - Example of multifilament bobbin of "9" Fibre 5.

3.1.5 Spinnability test compound II. PBS/PHA

At the temperature of 120 °C, Compound II. PBS/PHA showed a moisture content of zero.

Spinning trials were carried out at different temperature profiles, producing six different fiber typologies, applying different stretches (**Table 14**).

Other parameters used in the production of these fibres are detailed in "Annex I - parameters related to the extrusion process".

Table 14 - Compound II. PBS/PHA extrusion temperature profile.

Temperature profile	Fibre reference	Extruder heating zones (°C)			Melt pump (°C)	Melt temperature (°C)	Transfer line (°C)	Spinnert (°C)	Speed (rpm)	Pressure (bar)
		1	2	3						
II. PBS/PHA T1	Not spinnable	165	193	205	210	206	210	210	30	0
II. PBS/PHA T2	"II" Fibre 1 "II" Fibre 2	160	183	191	189	189	163	210	30 / 7,6	0
II. PBS/PHA T3	"II" Fibre 3 "II" Fibre 4	150	165	170	180	177	163	200-210	30	14-19
II. PBS/PHA T4	"II" Fibre 5 "II" Fibre 6	150	165	168	180	177	160	190	30	23-28

This material presented a suitable flow rate and stability under melt-spinning process. The multifilaments "II" Fibre 5 and "II" Fibre 6 were obtained under the most stable temperature profile (T4) and they were used for characterization comparisons since the material was in conditions to be stretched to its limits. **Table 15** provides the spinning parameters of each collected multifilament, **Figure 10** is an example of one multifilament bobbin, specifically "II" Fibre 4.

Table 15 - Compound 11. PBS/PHA spinning parameters of fibres.

Fibre reference	Throughput (g/min)	Rolls speed (m/min)			Rolls temperature (°C)			DDR (V1/V0)	CDR (V2/V1)
		R1	R2	R3	R1	R2	R3		
"11" Fibre 1*	5.47	93	140	136	57	35	27	207	1.51
"11" Fibre 2*	5.47	167	220	213	51	36	27	372	1.32
"11" Fibre 3*	21.28	280	330	320	47	35	27	161	1.18
"11" Fibre 4*	21.28	280	540	508	47	35	28	161	1.93
"11" Fibre 5	21.28	601	975	897	45	35	28	345	1.62
"11" Fibre 6	21.28	100	250	225	45	37	28	57	2.50

* Fibres obtained under an unstable spinning process that may lack filaments and possess other defects.



Figure 10 - Example of multifilament bobbin of "11" Fibre 4.

3.1.6 Spinnability test compound 12. Starch/PBAT:PHA

Before spinning, compound 12 was also subjected to moisture content measurement. Given the low melt temperature of this material, the measure was carried out at 110 °C, showing a moisture content of 0.1139 ± 0.0258% (around 1139 PPM).

Parameters of processing of different temperature profiles are listed in **Table 16**. Since at T1 the material started to degrade, after lowering the temperatures to T2, the material presented a suitable flow rate and stability under the melt-spinning process and it was possible to obtain several fibres under various stretches (**Table 17**). The different multifilaments obtained from this compound are shown in **Figure 11**. Other parameters related to the extrusion process, calculated shear rates, torques and pressure for each trial are specified in "Annex I - parameters related to the extrusion process".

It was also noticed that this blend is temperature sensitive, at a throughput below 15 rpm, it has a high tendency to degrade, as shown in **Figure 12**.

Table 16 - Compound 12. Starch/PBAT:PHA extrusion temperature profile.

Temperature profile	Fibre reference	Extruder heating zones (°C)			Melt pump (°C)	Melt temperature (°C)	Transfer line (°C)	Spinnert (°C)	Speed (rpm)	Pressure (bar)
		1	2	3						
12. Starch/PBAT:PHA T1	Not spinnable	165	180	185	190	185	165	175	30	9
12. Starch/PBAT:PHA T2	"12" Fibre 1 to "12" Fibre 4	160	175	180	180	180	155	150	30	30-38

Table 17 - Compound 12. Starch/PBAT:PHA spinning parameters of fibres.

Fibre reference	Throughput (g/min)	Rolls speed (m/min)			Rolls temperature (°C)			DDR (V1/V0)	CDR (V2/V1)
		R1	R2	R3	R1	R2	R3		
"12" Fibre 1	21.28	100	240	233	48	35	28	57	2.41
"12" Fibre 2	21.28	610	850	816	42	35	28	350	1.39
"12" Fibre 3	21.28	610	830	800	43	35	29	350	1.36
"12" Fibre 4	21.28	610	615	612	44	35	29	350	1.01

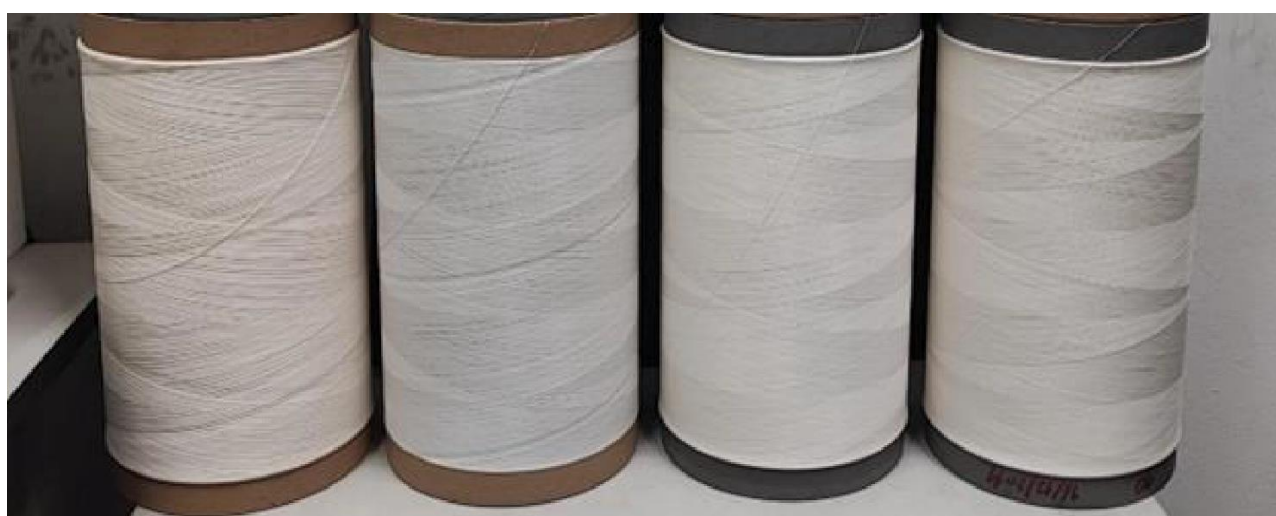


Figure 11 - Multifilaments obtained from compound 12. Starch/PBAT:PHA



Figure 12 - Representation of the degradation that occurs at low extrusion speeds for compound 12. Starch/PBAT:PHA.

3.1.7 Spinnability test compound 13. Starch/PBAT

Compound 13 shows a moisture content of 0.0857 ± 0.0068 % (around 857 PPM) which is usually high for the melt spinning process. However, this material was also able to form continuous filaments at several stretching ratios. The processing temperature profiles are detailed in **Table 18**.

Table 18 - Compound 13. Starch/PBAT extrusion temperature profile.

Temperature profile	Fibre reference	Extruder heating zones (°C)			Melt pump (°C)	Melt temperature (°C)	Transfer line (°C)	Spinnert (°C)	Speed (rpm)	Pressure (bar)
		1	2	3						
13. Starch/PBAT T1	Not spinnable	160	175	180	180	180	155	150	30	100
13. Starch/PBAT T2	"13" Fibre 1 to "13" Fibre 4	160	178	180	180	183	155-160	160	30	96-99
13. Starch/PBAT T3	Not spinnable	165	185	190	195	186	185	170	30	94

Initially, compound 13 was processed using temperature profile T1, setting the same processing parameters as compound 12 under T1 conditions. As expected, the pressure registered for compound 13 was higher than that of compound 12, due to its greater viscosity. To optimize processing, a slightly higher temperature profile (T2) was subsequently applied. Thanks to the higher apparent melt strength of compound 13, it was possible to achieve higher spinning speeds compared to those obtained with compound 12. The spinning parameters of multifilaments obtained from compound 13 are presented in **Table 19** and **Figure 13** shows the different obtained fibres. Other parameters related to the extrusion process, calculated shear rates, torques and pressure for each trial are specified in "Annex 1 - parameters related to the extrusion process".

Table 19 - Compound 13. Starch/PBAT spinning parameters of fibres

Fibre reference	Throughput (g/min)	Rolls speed (m/min)			Rolls temperature (°C)			DDR (V1/V0)	CDR (V2/V1)
		R1	R2	R3	R1	R2	R3		
“13” Fibre 1	23.06	650	655	652	43	35	30	373	1.01
“13” Fibre 2	23.06	630	635	632	43	35	30	361	1.01
“13” Fibre 3	23.06	630	1050	987	45	35	30	361	1.67
“13” Fibre 4	23.06	100	210	200	45	35	30	57	2.10



Figure 13 - Multifilaments obtained from compound 13. Starch/PBAT

3.2 Mechanical characterization

3.2.1 Linear density

Linear density was evaluated according to *ISO 2060: Textiles — Yarn from packages — Determination of linear density (mass per unit length)* by the skein method. Three samples from each fibre were measured. Linear density is a key parameter which influence mechanical performance as tenacity. **Table 20** summarizes linear density values of all the multifilaments obtained by all the compounds, except Compound 8 which resulted to be not suitable for melt spinning. Filaments obtained under stable conditions are highlighted in the table.

Table 20 - Linear density values.

Fibre reference	Throughput (g/min)	DDR (V1/V0)	CDR (V2/V1)	Linear Density dtex (g/10000 m)
“2” Fibre 1	21.28	57	2.10	1073 ± 19
“2” Fibre 2*	21.28	72	1.80	920 ± 16



“2” Fibre 3	21.28	69	1.88	913 ± 17
“6” Fibre 1*	23.06	17.18	1.13	6507 ± 121
“6” Fibre 2*	23.06	17.18	1.13	5473 ± 351
“9” Fibre 1*	21.28	57	1.15	1533 ± 12
“9” Fibre 2	21.28	57	1.10	1720 ± 20
“9” Fibre 3*	21.28	358	1.15	245 ± 32
“9” Fibre 4	21.28	353	1.16	261 ± 2
“9” Fibre 5	21.28	353	1.00	289 ± 15
“11” Fibre 1*	5.47	207	1.51	540 ± 0
“11” Fibre 2*	5.47	372	1.32	207± 9
“11” Fibre 3*	21.28	161	1.18	595 ± 0
“11” Fibre 4*	21.28	161	1.93	227 ± 0
“11” Fibre 5	21.28	345	1.62	223 ± 5
“11” Fibre 6	21.28	57	2.50	860 ± 0
“12” Fibre 1	21.28	57	2.41	937 ± 31
“12” Fibre 2*	21.28	350	1.39	250 ± 0
“12” Fibre 3	21.28	350	1.36	250 ± 3
“12” Fibre 4	21.28	350	1.01	315 ± 12
“13” Fibre 1*	23.06	373	1.01	295 ± 5
“13” Fibre 2	23.09	361	1.01	337 ± 12
“13” Fibre 3	23.06	361	1.67	220 ± 8
“13” Fibre 4	23.06	57	2.10	1103 ± 25

* Fibres obtained under an unstable spinning process that may lack filaments and possess other defects.

3.2.2 Tenacity and tensile properties

Mechanical tests were performed according to *ASTM D 3822:07 - Standard Test Method for Tensile Properties of Single Textile Filaments*, using a universal mechanical test machine (Shimadzu AGX-V 50 kN, **Figure 14**), with a 100 N load cell. Tests were carried out 7 days after production on 10 specimens for each multifilament, test speed was set at 250 mm/min and gauge length at 25 mm. Elongation at break and force at break have been registered to determine the filament tenacity. **Table 21** presents mechanical characterization results for each material. Filaments obtained under stable conditions are highlighted in the table.





Figure 14 - Shimadzu universal mechanical test machine.

Table 21 - Mechanical characterization results.

Fibre reference	Stretching Conditions	Force at break (cN)		Tenacity (cN/dtex)		Elongation at break (%)	
		Av.	σ	Av.	σ	Av.	σ
“2” Fibre 1	DDR-, CDR+	826	49	0.77	0.05	175	14
“2” Fibre 2*	Unstable	739	12	0.80	0.01	171	13
“2” Fibre 3	DDR+, CDR+	690	29	0.76	0.03	165	23
“6” Fibre 1*	Unstable	3015	220	0.46	0.03	571	70
“6” Fibre 2*	Unstable	2874	234	0.53	0.04	740	139
“9” Fibre 1*	Unstable	818	76	0.53	0.07	153	47
“9” Fibre 2	DDR-, CDR+	860	107	0.50	0.10	249	59
“9” Fibre 3*	Unstable	228	14	0.93	0.01	58	7
“9” Fibre 4	DDR+, CDR+	274	14	1.05	0.01	58	6
“9” Fibre 5	DDR+, CDR=1	229	7	0.79	0.01	81	6
“11” Fibre 1*	Unstable	201	14	0.37	0.03	458	55



“11” Fibre 2*	Unstable	99	4	0.48	0.02	201	44
“11” Fibre 3*	Unstable	398	9	0.67	0.01	381	61
“11” Fibre 4*	Unstable	357	14	1.57	0.06	176	25
“11” Fibre 5	DDR+, CDR+	264	16	1.18	0.07	118	5
“11” Fibre 6	DDR-, CDR+	1061	17	1.23	0.02	257	16
“12” Fibre 1	DDR-, CDR+	417	28	0.45	0.03	203	15
“12” Fibre 2*	Unstable	129	6	0.51	0.01	103	16
“12” Fibre 3	DDR+, CDR+	125	6	0.50	0.01	107	13
“12” Fibre 4	DDR+, CDR=1	119	5	0.38	0.01	143	17
“13” Fibre 1*	Unstable	132	3	0.45	0.00	130	14
“13” Fibre 2	DDR+, CDR=1	126	8	0.37	0.01	109	17
“13” Fibre 3	DDR+, CDR+	142	3	0.64	0.00	55	7
“13” Fibre 4	DDR-, CDR+	503	13	0.46	0.01	188	10

* Fibres obtained under an unstable spinning process that may lack filaments and possess other defects.

3.3 Discussion

Figure 15 shows a comparison of force at break, linear density and tenacity values of all the produced multifilament obtained under stable conditions. The multifilament “11” Fibre 6 registered the maximum value of force at break (1061 cN) and the maximum value of tenacity (1.23 cN/dtex).

The multifilament was obtained under the best stretching conditions (DDR-, CDR+) to achieve the highest tenacity for the material: the minimum hot stretching (DDR-), followed by the maximum cold-stretching (CDR+). A promising result has been also obtained in terms of tenacity for compound 9 (1.05 cN/dtex), even if with a low force at break (“9” Fibre 4). It is important to highlight that when compared to the target values for tenacity and tensile strain at break of fossil-based yarns (**Table 1**), the obtained values are below acceptable levels.

In addition, considering elongation at break results (**Figure 16**), all the registered values resulted to be significantly higher than the target value, which is represented in the graph by a horizontal red line (19.5 %).

Elongation at break is another important mechanical parameter, since reflects the material ability to deform under tensile stress before breaking, which is essential in applications where dynamic loads and repeated mechanical stresses are common. Even if sufficient elongation at break ensures net flexibility, durability and resistance to tearing, an excessive elongation at break is not desirable, as it may lead to excessive deformation



of the net structure under load, causing loss of shape, and reduced dimensional stability, which can affect the mesh size and compromise the functionality of the net during operation.

Therefore, an optimal balance between elongation and tenacity is required, ensuring the net is both strong and dimensionally stable without being prone to either brittleness or excessive stretching.

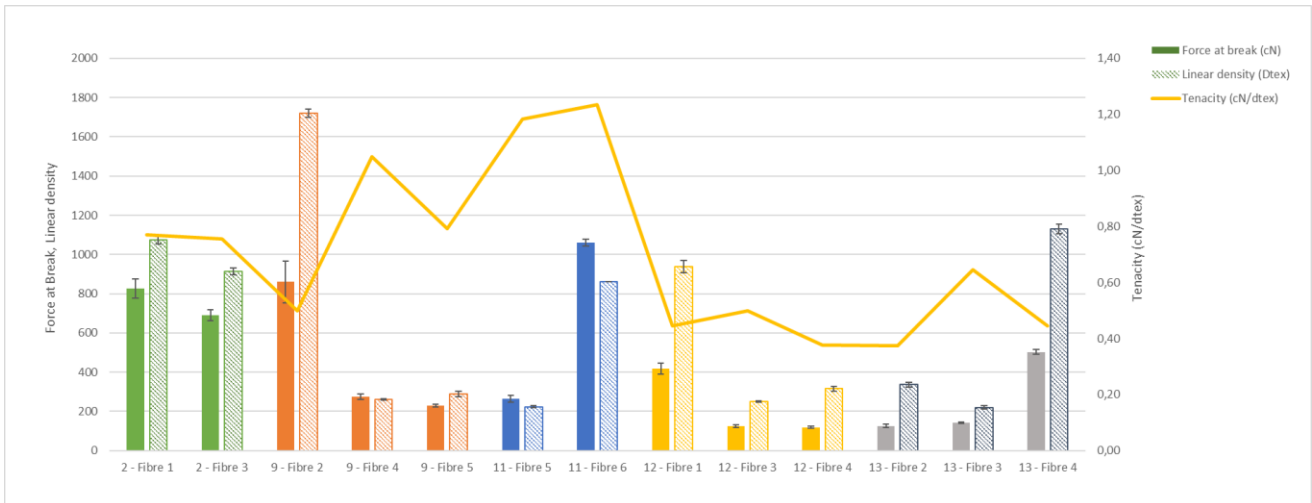


Figure 15 - Comparison of force at break, linear density and tenacity values between all the multifilaments obtained under stable processes.

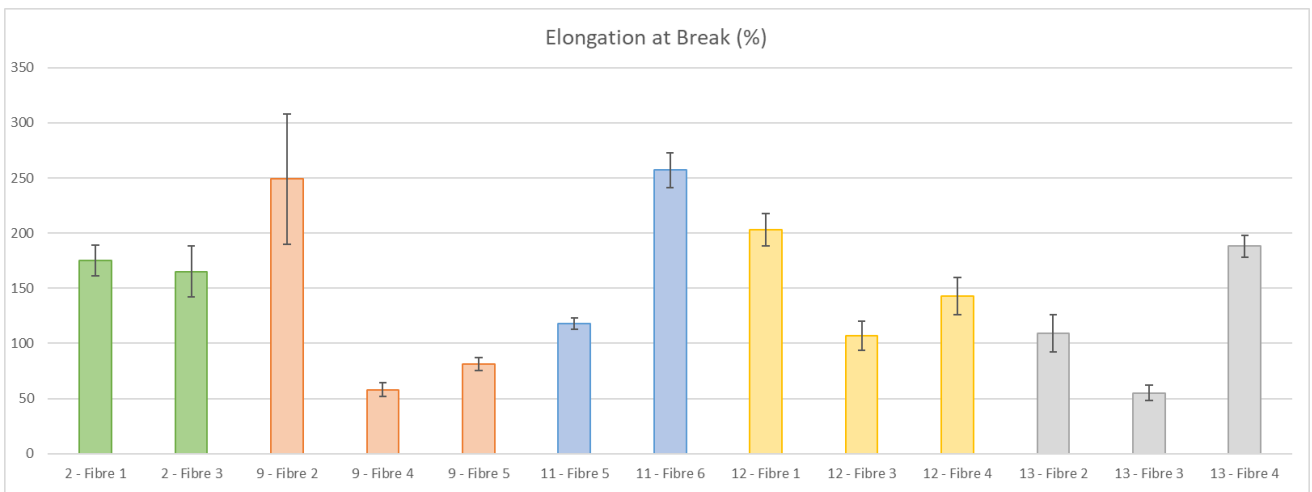


Figure 16 - Comparison of elongation at break values between all the multifilaments obtained under stable processes.

3.4 Conclusions

All seven selected compounds were tested with multifilament melt spinning process. Among them, only compound 8. PLA/PBS resulted to be not suitable for the process, and no samples were collected. From all the other compounds, at least two fibers were produced. Based on the results, compound 11. PBS/PHA and compound 9. PLA/PCL demonstrated the most promising performance in terms of process stability for multifilament production.

Due to the higher viscosity and low MFR observed in processing of compounds 2. PBS/PBAT and 6. PBS/PBAT, these materials are prone to filament breakage at higher draw-down ratios. Filament production was only possible by applying spinning speeds below the typical operational range for the melt-spinning process. Consequently, these compounds are considered more suitable for processes that operate at lower speeds, such as horizontal monofilament extrusion. Compound 9. PLA/PCL can be also considered for monofilament production.

Compounds 12. Starch/PBAT:PHA and 13. Starch/PBAT demonstrated good processability, reaching spinning speeds as high as 1050 m/min, the highest among all materials tested. However, despite their compatibility with high-speed spinning, both compounds exhibited poor mechanical performance, with the lowest tenacity values recorded. In particular, compound 13. Starch/PBAT achieved a tenacity of only 0.64 cN/dtex, highlighting the limitations of these materials in applications where mechanical strength is critical.

However, these results in terms of tenacity are still significantly below the target parameters for multifilament, as outlined in [Table 1](#). Further improvements of the formulations are needed, considering promising results of compound 11. PBS/PHA and compound 9. PLA/PCL.

4 Laboratory scale monofilament production: first phase

As discussed in [Chapter 3](#), compound 2. PBS/PBAT and 6. PBS/PBAT and compound 9. PLA/PCL were considered as possible candidate for monofilament production. Based on the results, compound 2. PBS/PBAT and compound 9. PLA/PCL were selected by NTT, since compound 6. PBS/PBAT resulted in stability issues during the process trials, including during the production of the two collected multifilaments (“6” Fibre 1 and “6” Fibre 2).

In addition to target parameters of [Table 1](#), CIT reported that the most common traditional fossil-based monofilaments for fishing nets production have usually filament diameters between 200 and 350 μm .

4.1 Spinning trials

BIO-MI provided NTT with three samples of 4 kg each of compound 2. PBS/PBAT, compound 2.1 PBS/PBAT and compound 9. PLA/PCL to be tested with horizontal monofilament extrusion process.

For this round of trials Bio-Mi prepared 3 different blends coded **Remedies 2** (PBS 50: PBAT 50), **Remedies 2.1** (PBS- injection moulding grade 50: PBAT 50) and **Remedies 9** (PLA 70: PCL 30). As already mentioned, during every testing trial Bio-Mi followed same methodology and protocols where most important step (except twin screw extrusion) was characterization of raw materials and characterization of obtained blends following relevant standards. Obtained granules were characterized for density (ASTM D792), moisture (ASTM 6980), melt flow rate (ISO 1133), and DSC (ASTM D3418). It is worth to mention that compounding stage temperatures were same as in previous trials, between 110-160°C. During compounding step everything ran smoothly.

Table 22 - Results of characterization during third round of trials

Parameter	Remedies 2	Remedies 2.1	Remedies 9
T_m , °C	114.1	114.4	61.5 / 147.2
MFR, g/10 min 190 °C, 2.16 kg	7.2	14.0	9.8
Density, g/cm ³	1.26	1.25	1.18
Moisture, %	0.432	0.438	0.418



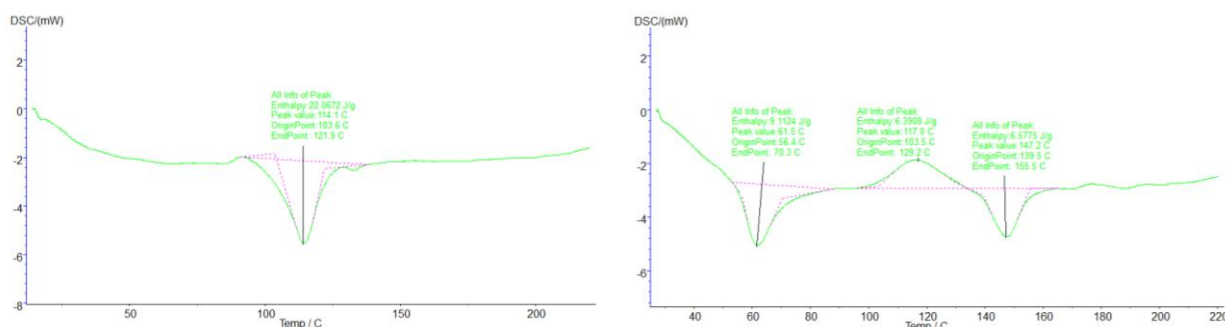


Figure 17 - DSC thermograms of Remedies 2 (left) and Remedies 9 (right) compounds 1st heating

At the end, all three blends were shipped to NTT for the repetition of processing trials in order to find the best formulations. The main focus was on good processability and adequate mechanical properties.



Figure 18 - Samples of materials shipped to NTT

Given the high MFR of compound 2.1, which is a result of its PBS injection moulding grade, it was determined that this sample would not be suitable for spinning testing. The elevated MFR indicates a lower viscosity, making the material less compatible with the intended processing conditions. As a result, the decision was made to exclude this sample from the testing phase.

Prior processing by NTT, both materials were dried for 14h at 65°C and T_m and MFR were measured as reported in **Table 23**.

Table 23 - Compounds selected for spinnability trials and their properties.

Compound	T_m (°C)	MFR (g/10 min) 190 °C, 2.16 kg
2. PBS/PBAT	116.3	5.0
9. PLA/PCL	147.4 / 60.4	7.8

The extrusion trials were carried out on lab-scale equipment.

Trials were performed using a Periplast single screw extruder, equipped with a 90-degree extrusion head, with a 1.25 mm diameter die attached (6 mm in length), a water bath, three roll stands with 5 stretching rolls each, 2 heated chambers (for stretching and stabilization) and a winder.

The monofilament extrusion line scheme is illustrated in **Figure 19**.

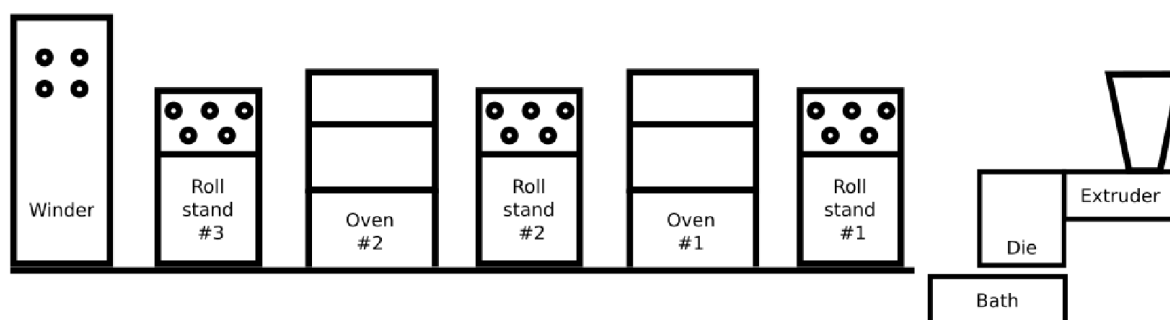


Figure 19 - Monofilament extrusion line scheme.

Each material was tested according to the following steps:

- Spinning temperatures: the temperatures were adjusted to achieve optimal process stability;
- Throughput: the maximum possible without defects such as overflow, shark skin, melt fracture, over-pressure or screw effort was experimentally determined, also considering the available quantities of material;
- Draw ratios: these values were adjusted to enhance the mechanical performance, namely the filament tenacity;
- Samples: if a stable process was achievable, it was intended to obtain samples from each material (bobbins), with a length of at least 200 m;
- Target:
 - Filament diameter: targeted filament diameters between 200 and 350 μm ;
 - Tenacity: maximization of tenacity value for each material, for the filament diameter achieved.

4.1.1 Monofilament extrusion test compound 2. PBS/PBAT

At the temperature of 120 °C, the material showed a moisture content of zero.

Using temperature profile T1, the compound demonstrated a stable flow rate and stability under the monofilament extrusion, confirming its suitability for this process. It was possible to apply different draw ratios, producing filament diameters ranging from 250 to 300 μm . **Table 24** presents the extrusion temperature profile of the process.

At higher draw ratios, the process became unstable, and only a few meters of “2” Filament 2 with a diameter of 250 μm were successfully collected.

Under stable processing conditions, more than 200 m of “2” Filament 1 were produced. During both trials, multiple diameter measurements were taken along the length of the filaments using a micrometer. The obtained filaments are shown **Figure 20** and drawing parameters are listed in **Table 25**.

Table 24 - Extrusion temperature profile for compound 2. PBS/PBAT

Temperature profile	Filament reference	Extruder heating zones ($^{\circ}\text{C}$)			Die ($^{\circ}\text{C}$)	Oven #1	Oven #2
		1	2	3			
2. PBS/PBAT T1	“2” Filament 1 “2” Filament 2	170	175	180	180	125	55

Table 25 - Drawing parameters for the filaments obtained with compound 2. PBS/PBAT

Filament reference	Throughput (g/min.)	Rolls speed (m/min)			Draw ratio #1 (R2/R1)	Draw ratio #2 (R3/R2)	Filament diameter (μm)
		Roll stand #1 (R1)	Roll stand #2 (R2)	Roll stand #3 (R3)			
“2” Filament 1	4.5	5.2	26	35	5.0	1.3	300
“2” Filament 2*		5.2	35	44	6.7	1.3	250

* Filament obtained under an unstable spinning process that may lack filaments and possess other defects.



Figure 20 – Compound PBS/PBAT: “2” Filament 1 (left) and “2” Filament 2 (right).

4.1.2 Monofilament extrusion test compound 9. PLA/PCL

At the temperature of 120 °C, the material showed a moisture content of zero.

Using temperature profile T1, the compound presented a stable flow rate and stability under the monofilament extrusion, confirming its suitability for this process. The maximum achievable draw ratios were applied, resulting in a filament diameter of 300 µm. More than 300 meters of “9” Filament 1 were obtained under a stable process.

With the increased temperature profile T2, higher draw ratios were attempted. However, the process exhibited instability after only a few meters, and the filament diameter remained at 300 µm, indicating no significant reduction despite the elevated draw ratio. **Table 26** presents T1 and T2 temperature profiles. During both trials, multiple diameter measurements were taken along the length of the filaments using a micrometer. The obtained filaments are shown **Figure 21** and drawing parameters are listed in **Table 27**.

Table 26 - Extrusion temperature profile for compound 9. PLA/PCL

Temperature profile	Filament reference	Extruder heating zones (°C)			Die (°C)	Oven #1	Oven #2
		1	2	3			
9. PLA/PCL T1	9” Filament 1	155	160	165	165	110	40
9. PLA/PCL T2	“9” Filament 2	175	180	185	185	110	40

Table 27 - Drawing parameters for the filaments obtained with compound 9. PLA/PCL

Filament reference	Throughput (g/min.)	Rolls speed (m/min)			Draw ratio #1 (R2/R1)	Draw ratio #2 (R3/R2)	Filament diameter (µm)
		Roll stand #1 (R1)	Roll stand #2 (R2)	Roll stand #3 (R3)			
“9” Filament 1	5.5	5.2	39	41	7.5	1.1	300
“9” Filament 2*		7.6	47	51	6.2	1.1	300

* Filament obtained under an unstable spinning process that may lack filaments and possess other defects.



Figure 21 - Filaments obtained from compound 9. PLA/PCL

4.2 Mechanical characterization

4.2.1 Linear density

Linear density was evaluated according to *ISO 2060: Textiles — Yarn from packages — Determination of linear density (mass per unit length)* by the skein method. Three samples from each fibre were measured. Filaments obtained under stable conditions are highlighted in **Table 28**.

Table 28 - Linear density values.

Filament Reference	Throughput (g/min)	Draw ratio #1 (R2/R1)	Draw ratio #2 (R3/R2)	Quantity of filament (m)	Linear Density - dtex (g/10000 m)
"2" Filament 1	4.5	5.0	1.3	± 200	1281 ± 8
"2" Filament 2*		6.7	1.3	± 20	1017 ± 42
"9" Filament 1	4.5	7.5	1.1	± 300	1424 ± 15
"9" Filament 2*		6.2	1.1	± 70	1066 ± 18

* Filament obtained under an unstable spinning process that may lack filaments and possess other defects.

4.2.2 Tenacity and tensile properties

Mechanical tests were performed according to *ASTM D 3822:07 - Standard Test Method for Tensile Properties of Single Textile Filaments*, using a universal mechanical test machine (Shimadzu AGX-V 50 kN, **Figure 14**), with a 100 N load cell. Tests were carried out 7 days after production on 10 specimens for each multifilament, test speed was set at 250 mm/min and gauge length at 25 mm. Elongation at break and force at break have been registered to determine the filament tenacity. **Table 29** - Mechanical characterization results presents mechanical characterization results for each material. Filaments obtained under stable conditions are highlighted in the table.

Table 29 - Mechanical characterization results

Filament Reference	Filament Diameter (μm)	Force at break (cN)		Tenacity (cN/dtex)		Elongation at break (%)	
		Av.	σ	Av.	σ	Av.	σ
“2” Filament 1	300	4040	16	3.15	0.01	149	3
“2” Filament 2*	250	3571	14	3.51	0.01	154	9
“9” Filament 1	300	3375	164	2.37	0.12	98	6
“9” Filament 2*	300	2841	165	2.67	0.15	114	13

* Filament obtained under an unstable spinning process that may lack filaments and possess other defects.

4.3 Discussion

Figure 22 shows the comparison of mechanical properties of the four obtained monofilaments. Compound 2. PBS/PBAT registered the best mechanical properties in terms of tenacity and force at break compared to compound 9. PLA/PCL, even considering filaments obtained with stable and unstable processes. Focusing on stable processes, the highest values were recorded for “2” Filament 1, with a Force at Break of 40.4 N and a tenacity of 3.15 cN/dtex. However, “2” Filament 1 and in general compound 2. PBS/PBAT, registered the highest values of elongation at break which, as discussed for multifilament in Paragraph 3.2.2, may have a negative impact on net production process and the mechanical performance of the final product. When compared to the target monofilament values in **Table 1**, the tenacity of compound 2. PBS/PBAT, although slightly lower than desired, remains acceptable due to its excellent force at break. In contrast, its elongation at break is approximately six times higher than the specified target.

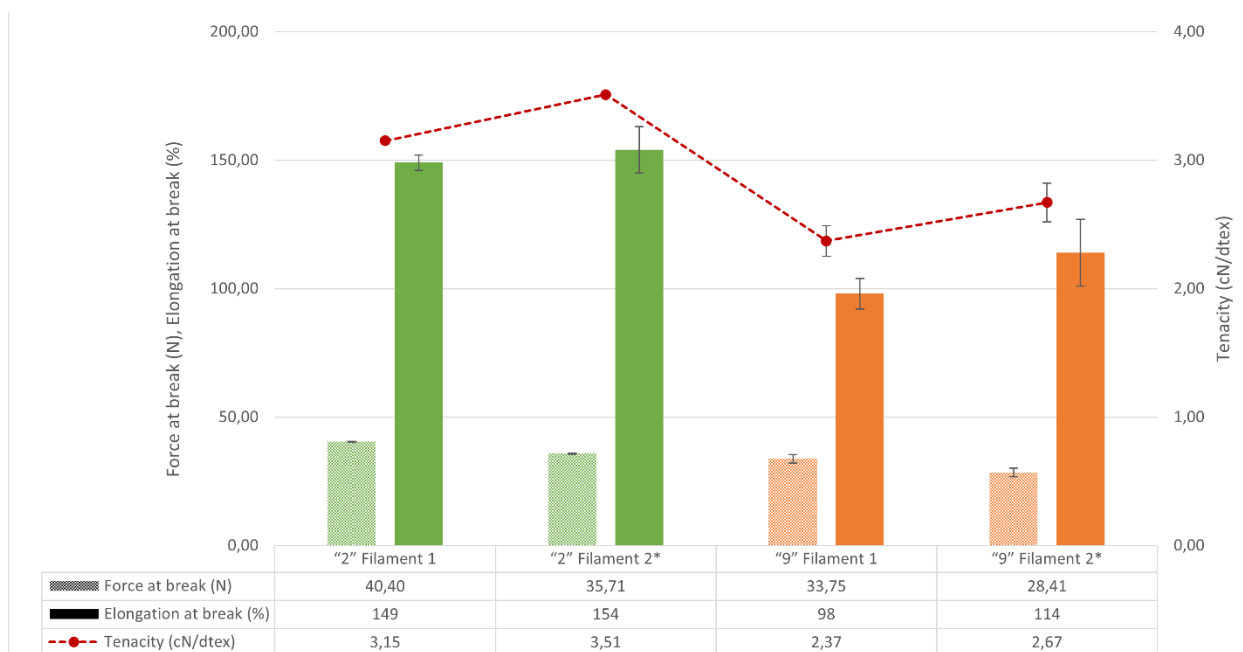


Figure 22 - Comparison of force at break, elongation at break and tenacity values between all the monofilaments obtained from compounds 2. PBS/PBAT and 9. PLA/PCL.

4.4 Incorporation of Lignin as a Natural UV-Absorbing Additive

CNR proposed an additional strategy to improve stability of these polymeric materials under UV exposure and, at the same time, maintaining the sustainability of the products. In this respect, lignin, a natural UV-absorbing compound, was introduced into PBS/PBAT polymer blends. Thanks to its intrinsic ability to absorb ultraviolet radiation, lignin is expected to enhance the photodegradability of the material when exposed to sunlight in marine environments.

Based on previous results, the Compound 2. PBS/PBAT 85:15 blend was selected as a base matrix for the incorporation of lignin as a filler. A series of formulations were prepared by varying the lignin content at different concentrations, as reported in **Table 30**.



Table 30 - PBS/PBAT blends with different amount of lignin

BLEND	LIGNIN (PHR)
PBS/PBAT 85:15	0
PBS/PBAT 85:15	0.1
PBS/PBAT 85:15	0.5
PBS/PBAT 85:15	1
PBS/PBAT 85:15	2.5
PBS/PBAT 85:15	5

All formulations were prepared using Brabender internal mixer, Plastograph EC (Brabender GmbH & co. kg, Germany) and the mixing process was carried out at 180°C and 60 rpm. The polymers and lignin powder were manually introduced into the preheated mixing chamber. Once homogeneous mixing was achieved, the material was manually recovered. The extrudate was then cooled and cut into smaller pieces using a pelletizer, to obtain uniform samples suitable for further testing. The blends were subsequently characterized through melt flow index (MFI) measurements and viscosity analysis using a rotational rheometer. Specifically, MFI testing was conducted at 180 °C under a 2.16 kg load, using a Ceast Melt Flow Junior 6943 melt flow index tester.



Figure 23 - Ceast Melt Flow Junior 6943 melt flow index tester



Approximately 5 grams of pelletized blend were loaded into the melt flow indexer. The instrument, through its integrated software, calculates the MFI based on the weight of the extrudate collected over a specific time interval. The results are reported in the **Table 31**.

Table 31 - MFI results for the different blends

BLEND	MFR_A (g/10min)
PBS/PBAT 85:15	5
PBS/PBAT 85:15 0.1 LIG	7.55
PBS/PBAT 85:15 0.5 LIG	10.31
PBS/PBAT 85:15 1 LIG	12.85
PBS/PBAT 85:15 2.5 LIG	19.26
PBS/PBAT 85:15 5 LIG	32.16

Viscosity tests were performed at 180 °C with a parallel plate geometry (25 mm diameter, 1 mm gap) under steady shear ranging from 0.5 s⁻¹ to 300 s⁻¹. The zero-shear viscosity values were identified and reported in **Table 32**. As the percentage of lignin present in the samples increases, there is an increase in melt flow, and a consequent decrease in viscosity, so the blends with the lowest percentage of lignin could be considered the most promising for the monofilament spinning process.

Table 32 - Viscosity zero shear rate values for the different formulations

BLEND	Viscosity ZEROSHEAR (Pa*s)
PBS/PBAT 85:15	3950±183
PBS/PBAT 85:15 0.1 LIG	3359 ±143
PBS/PBAT 85:15 0.5 LIG	1305±9
PBS/PBAT 85:15 1 LIG	1347± 88
PBS/PBAT 85:15 2.5 LIG	872±18
PBS/PBAT 85:15 5 LIG	300±39



4.5 Conclusions

Compound 2. PBS/PBAT and compound 9. PLA/PCL demonstrated suitable processability under monofilament extrusion conditions. A higher draw ratio was applied to compound 9. PLA/PCL, although under unstable processing conditions. The highest force at break tenacity and values were observed for Compound 2 (PBS/PBAT), with a maximum tenacity of 3.15 cN/dtex achieved under stable conditions in "2" Filament I. However, despite these positive results, the elongation at break exceeded the targeted threshold.



5 Blends for multifilament production: optimization phase

After first testing trials, CNR asked Bio-Mi team to provide them raw materials in order that they make optimization of the blends. Firstly, in focus were blends no.9 PLA:PCL and no.11 PBS:PHA. The aim of new tests was to obtain higher tenacity results. Therefore, Bio-Mi provided PLA (injection moulding grade LI05), PLA (extrusion grade LX175), PBS (FZ91PM), PHBV (Y1000P), PCL (Capa 6500D), cellulose fibres and filler talc.



Figure 24 - Samples of materials shipped to CNR for further optimization

According to the spinning tests for multifilament in chapter 3, the compound 9, the PLA/PCL blend, has emerged as one of the most promising solutions for this purpose. In order to optimize the formulation CNR has prepared, in laboratory scale, different blends having different weight ratios of PLA/PCL. The blends are shown in the Table 33.

Table 33 - PLA/PCL blends.

Polymer matrix	Composition
PLA/PCL	70:30
PLA/PCL	80:20
PLA/PCL	90:10

5.1 Preparation of blends

Polymer blends were prepared starting polymers supplied by BIOMI using a mini-extrusion process. The blends were prepared using a Thermo HAAKE MiniLab twin screw extruder (Thermo Scientific, Karlsruhe, Germany) reported in **Figure 25**, operating in continuous mode for 10 min setting a temperature of 180°C at n=40rpm.



Figure 25 - Thermo HAAKE MiniLab twin screw extruder.

The selected polymers were carefully weighted and introduced into the feed hopper of a twin-screw mini-extruder, preheated to the appropriate processing temperature. The extrusion parameters were optimised to ensure efficient mixing and homogenization of the components. Upon exiting the die, the extrudate was manually collected and immediately cut into smaller segments to form pellets. This step was carried out while the extrude was still in a semi-molten or soft state, to facilitate clean cutting and obtain pellets of relatively uniform dimensions. The freshly formed pellets were then allowed to cool to room temperature under ambient conditions. The resulting pelletized blends were subsequently subjected to a series of characterization techniques as Melt Flow Index and Viscosity properties.

5.2 Rheological Characterization: Melt Flow Index and Viscosity Measurements

To evaluate the processability of PLA/PCL blends, rheological characterization was carried out through MFI measurement and viscosity analysis. MFI measurements were performed using a Ceast Melt Flow Junior 6943 melt flow index tester [Figure 23](#)

Approximately 5 grams of pelletized blend were loaded into the melt flow indexer. The test was performed at a constant temperature of 200°C, under an applied load of 2.16 kg, according to standard testing procedures. The instrument, through its integrated software, calculates the MFI based on the weight of the extrudate collected over a specific time interval. The results are reported in the [Table 34](#).

Table 34 - MFI results for the different blends.

BLEND	MFR_A (g/10min)
PLA/PCL 70:30	11.90
PLA/PCL 80:20	8.72
PLA/PCL 90:10	7.88

Complementary viscosity measurements were conducted using a rotational rheometer (Thermo Scientific Haake RheoStress 6000), equipped with parallel plate geometry (25 mm diameter and 1 mm gap). The tests were performed under static conditions, setting the temperature at 200°C to match the processing conditions used during the extrusion, and a controlled shear rate ranging from 0.5 s⁻¹ to 300 s⁻¹ was applied. Data analysis was carried out by extracting viscosity values at different shear rates using the rheometer's software. The obtained data were processed in Microsoft Excel, where the logarithm viscosity (Pa*s) was plotted against logarithm shear rate (s⁻¹), ([Figure 26](#) *Errore. L'origine riferimento non è stata trovata.*). From the resulting curves, the zero-shear viscosity values were identified and reported in [Table 35](#).

Table 35 - Viscosity results for the different blends.

BLEND	Viscosity _{ZEROSHEAR} (Pa*s)
PLA/PCL 70:30	1966 ± 189
PLA/PCL 80:20	1948 ± 102
PLA/PCL 90:10	894 ± 19

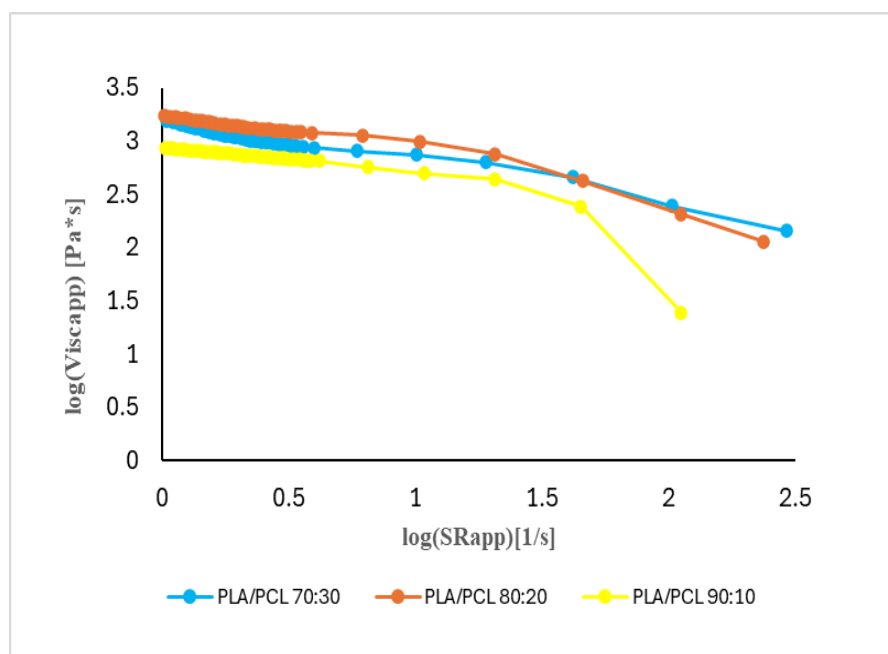


Figure 26 - Viscosity graphic of different composition of PLA/PCL

5.3 Preparation of Filler-Modified Blends

To enhance the tenacity of the polymer blends and improve their performance during the melt spinning process, selected fillers were incorporated into the formulations. The fillers chosen were cellulose and talc. The modified blends maintained the same polymer weight ratios as the original formulations. Cellulose was added at a concentration of 1 PHR, while talc was tested at two different loadings: 0.1 PHR and 5 PHR, in order to evaluate the effect of filler content on the resulting material properties. The different compositions are reported in **Table 36** :

Table 36 - PLA/PCL blend with filler.

BLEND	CNW(PHR)	TALC (PHR)
PLA/PCL 70:30	1	0.1-5
PLA/PCL 80:20	1	0.1-5
PLA/PCL 90:10	1	0.1-5

All blends with filler were prepared using the same twin-screw mini-extruder and following the procedure previously described. The extrusion process was performed at a constant temperature of 180°C and a speed of 40 rpm. The fillers were manually introduced during feeding by alternately polymer pellets and filler powder into the hopper, to promote homogeneous dispersion along the extruder.

The extrudates were manually collected and cut into pellets using the same method employed for the unfilled blends. These modified blends were subjected to the same rheological characterization protocols as the unfilled ones. To assess the effect of filler addition on material flow and processability under spinning-relevant conditions MFR and Viscosity tests were performed.

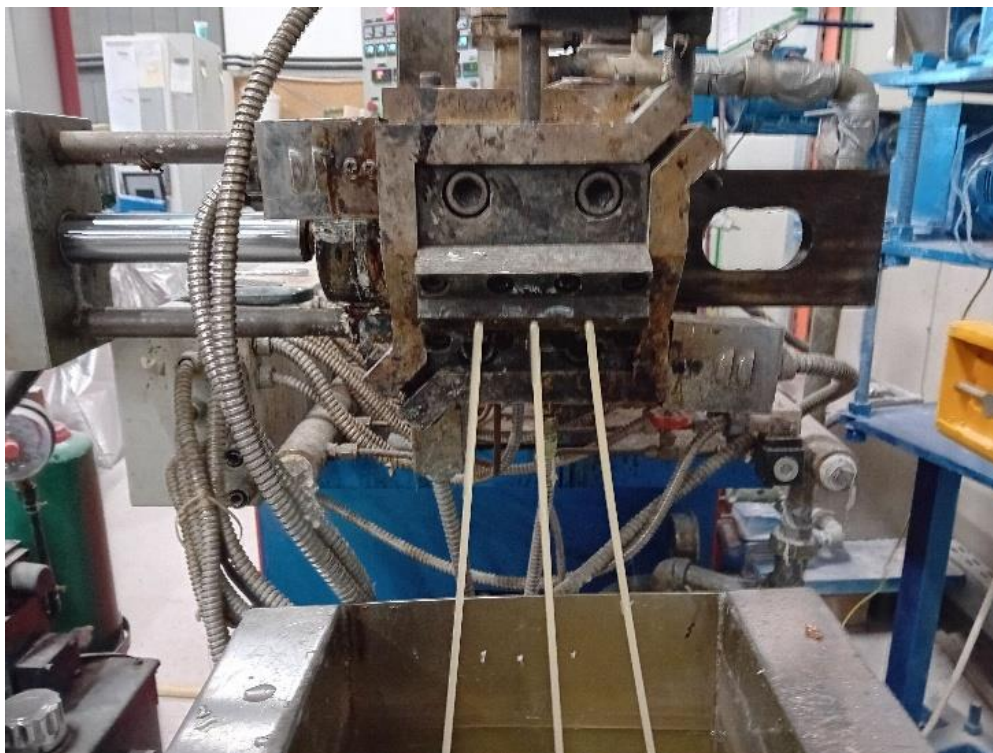


Figure 27 - Compounding of PLA:PCL with addition of cellulose fibres

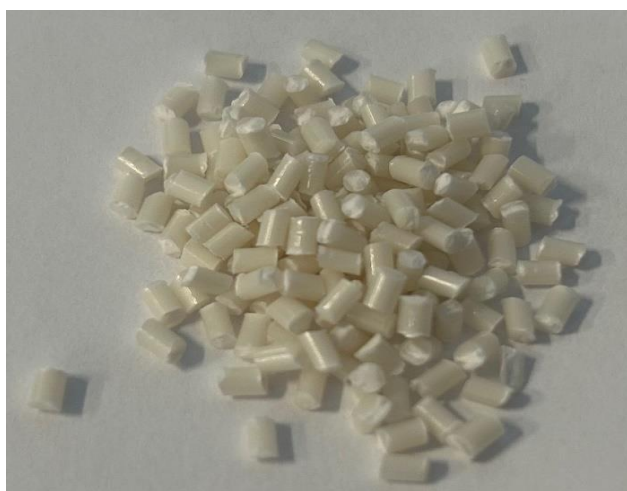


Figure 28 - PLA:PCL compounds with addition of talc (left) and with addition of cellulose fibres (right)

Results of characterization of obtained compounds during fourth group of trials are show in **Table 37**:

Table 37 - Characterization data of the compounds of PLA:PCL blends

Material	$T_m, ^\circ\text{C}$	MFR, g / 10 min 190 $^\circ\text{C}$, 2.16 kg	Density, g / cm ³	Moisture, %
PLA:PCL:Talc	602 / 145.4	9.7	1.2	0.3
PLA:PCL:CF	59.4 / 147.4	6.4	1.2	0.3

After the characterization, materials were shipped to NTT for further testing trials.

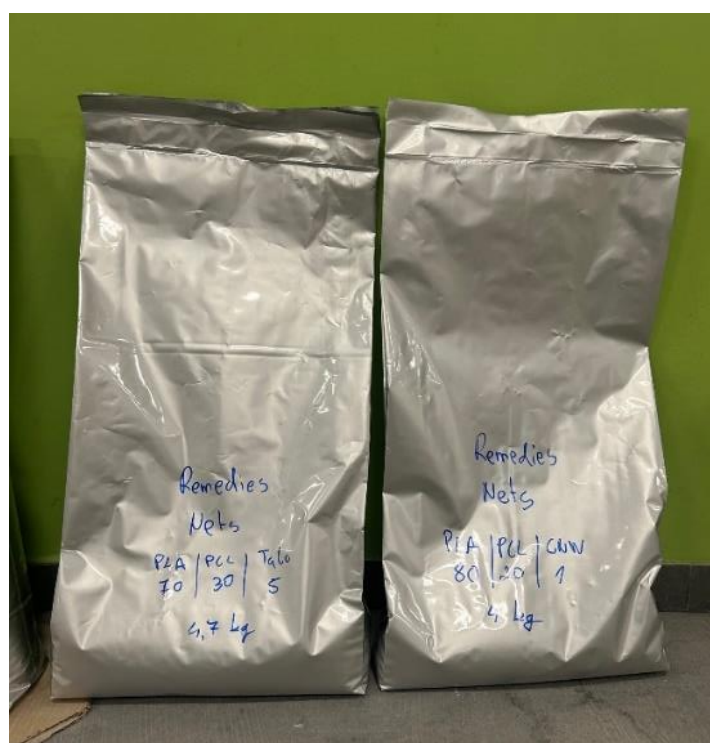


Figure 29 - Samples of PLA:PCL compounds with addition of talc and CNW

The MFR and viscosity results are reported below in **Table 38** and the graphic in **Figure 30**.



Table 38 - MFI and Viscosity results for the different materials.

BLEND	MFR_A (g/10min)	Viscosity ZEROSHEAR(Pa*s)
PLA/PCL 70:30 + 0.1 PHR TALC	16.88	1258±111
PLA/PCL 80:20 + 0.1 PHR TALC	9.52	1733±71
PLA/PCL 90:10 + 0.1 PHR TALC	7.95	1866±47
PLA/PCL 70:30 + 5 PHR TALC	12.01	1717±143
PLA/PCL 80:20 + 5 PHR TALC	11.19	1468±90
PLA/PCL 90:10 + 5 PHR TALC	9.18	1863±69
PLA/PCL 70:30 + 1 PHR CNW	10.73	1486±123
PLA/PCL 80:20 + 1 PHR CNW	9.04	1855±87
PLA/PCL 90:10 + 1 PHR CNW	7.38	2864±178



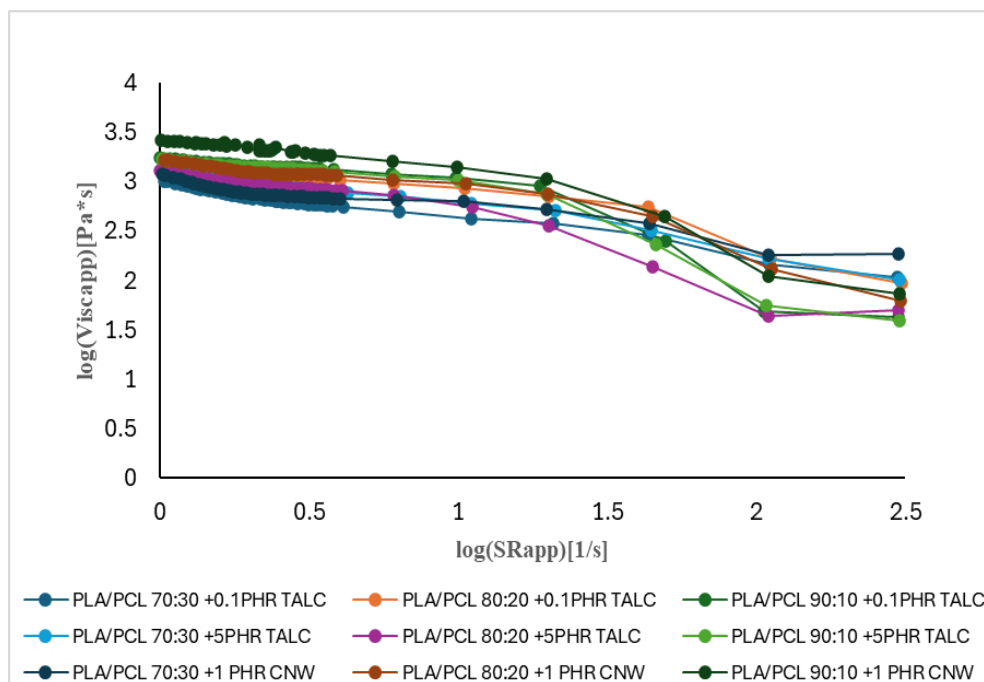


Figure 30 - Viscosity graphic of different materials

5.4 Conclusions

Various polymer blends based on compound 9 PLA/PCL were formulated and processed using a mini-extruder, including both unfilled systems and blends modified with talc and cellulose as functional fillers. Each formulation was subjected to rheological characterization.

The results demonstrated that the formulations with a good balance between MFR and viscosity were **PLA/PCL 70:30 + 5 PHR TALC** and **PLA/PCL 80:20 + 1 PHR CNW**.

PLA/PCL 70:30 + 5 PHR TALC showed the MFI similar to unfilled blend PLA/PCL 70:30 MFI, and a slight decrease of viscosity, suggesting that the addition of talc improves the processability of polymers.

PLA/PCL 80:20 + 1 PHR CNW exhibited MFI values compatible with the desired processing condition, and a decrease of viscosity suggesting that even the cellulose at a low quantity is a filler that can be used to increase the tenacity of polymer blends.



6 Laboratory scale multifilament production: second phase

The results of the first multifilament production phase ([Chapter 3](#)) highlighted that compound 9. PLA/PCL, for which PLA/PCL content was 70:30, showed very promising results. The next step of the study was carried out focusing on the tenacity increase.

Considering CNR tests discussed in Paragraph 5.4, two compounds were selected by NTT for the second phase of melt spinning, one with the addition of talc, and one with the addition of CNW:

- **Material A (PLA/PCL 70:30 + 5 PHR TALC)**: it seems to be the most promising, since in comparison with PLA/PCL 70:30 it has the same MFI and a slight decrease of viscosity;
- **Material B (PLA/PCL 80:20 + 1 PHR CNW)**: it seems the most promising with a slight decrease of viscosity.

6.1 Spinning trials

BIOMI provided NTT with 4 and 4.7 kg of Material A and Material B samples, respectively. [Table 39](#) presents a summary of the materials selected for the multifilament extrusion, which are characterized by the melting temperature (T_m) and the melt flow rate (MFR). Both materials were dried before the tests at 55°C/16h. At higher drying temperatures, the materials started to form agglomerates. The moisture content was measured after the drying of each material, with a moisture analyzer (Radweg MA 50/I.X2.A.WH), which has the sensibility to measure up to 1 part per million (ppm).

Table 39 - Compounds selected for second phase spinnability trials and their properties.

Ref.	Material	T_m (°C)	MFR (g/10 min) [190 °C, 2.16 kg]
Material A	PLA/PCL 70:30 + 5 PHR TALC	60.2 / 145.4	9.7
Material B	PLA/PCL 80:20 + 1 PHR CNW	59.4 / 147.4	6,4

The spinnability tests were carried out on a lab-scale equipment as described in [Paragraph 3.1](#).

Each material was tested according to the following steps:

- Spinning temperatures: Several temperatures were tested to achieve an optimal process stability and boost the filament's tenacity;
- Throughput: The maximum possible without defects such as overflow, shark skin, melt fracture, over-pressure or screw effort was experimentally determined;
- Take-up and draw speed: These values were adjusted to achieve the maximum tenacity;





- **Samples:** If a stable process was achievable, it was intended to obtain a sample (bobbins) with a length of at least 200 meters, under the following conditions:
 - (DDR-, CDR+): in this type of fibre, a very low hot stretching (DDR-) is applied, followed by the maximum cold stretching (CDR+), usually referred as drawing ratio. In these conditions, it's expected to achieve the highest tenacity for each material.

6.1.1 Spinnability test of Material A

At the temperature of 110 °C, the material showed a moisture content of zero.

Four different temperature profile were tested as shown in **Table 40**. Using the defined temperature profiles in combination with other parameters, such as extrusion velocities, feed roll temperature, shear rates and hot stretching (DDR), it was possible to achieve several draw ratios (CDR), listed in **Table 41**.

Figure 32 shows all the obtained bobbins. Other parameters used in the production of these fibres are detailed in “Annex I - parameters related to the extrusion process”.

Table 40 - Material A extrusion temperature profile.

Temperature profile	Filament reference	Extruder heating zones (°C)			Melt pump (°C)	Melt temperature (°C)	Transfer line (°C)	Spinneret (°C)	Throughput (g/min)	Pressure (bar)
		1	2	3						
A_T1	A_Filament 1	150	160	170	175	174	160	160	25.92	109
	A_Filament 2				165	8.64			50	
A_T2	A_Filament 3	134	149	145	161	158	145	143	25.92	128
A_T3	A_Filament 4	165	180	175	185	184	170	180	25.92	93
	A_Filament 5				185	85				
	A_Filament 6				185	86				
A_T4	A_Filament 7	165	185	180	185	195	170	185	25.92	102
	A_Filament 8				190	114				
	A_Filament 9				193	137				
	A_Filament 10				193	115				

Table 41 - Material A spinning parameters of filaments.

Filament reference	Throughput (g/min)	Rolls speed (m/min)			Rolls temperature (°C)			DDR (V1/V0)	CDR (V2/V1)
		R1	R2	R3	R1	R2	R3		
A_Filament 1*	25.92	90	165	162	64	39	28	42.39	1.83
A_Filament 2	8.64	90	120	118	67	44	28	127.18	1.33
A_Filament 3*	25.92	90	155	152	67	44	28	42.39	1.72





A_Filament 4	25.92	90	165	162	67	41	29	42.39	1.83
A_Filament 5*	25.92	90	210	208	80	40	29	42.39	2.33
A_Filament 6*	25.92	90	205	203	79	40	29	42.39	2.28
A_Filament 7*	25.92	90	380	380	98	40	26	42.39	4.22
A_Filament 8	25.92	90	285	285	98	40	26	42.39	3.17
A_Filament 9	34.56	90	305	305	101	41	27	31.79	3.39
A_Filament 10	25.92	90	285	299	101	41	27	42.39	3.32**

* Filament obtained under an unstable spinning process that may lack filaments and possess other defects.

** Drawn also between R2 and R3



Figure 31 – Spun bobbins of various A_Filament_x

6.1.2 Spinnability test of Material B

At the temperature of 110 °C the material showed a moisture content of zero.

The tested processing temperature profiles are listed in **Table 42**. The spinning trials with Material B were carried out using two different temperature profiles, T1 and T2. At the low-temperature profile (B_T1), no fibres could be collected, regardless of the throughput. A high throughput of 25.92 g/min resulted in high extrusion pressure, indicating that Material B requires a higher processing temperature.





When using the high-temperature profile (B_T2) and a low throughput of 8.64 g/min, it was possible to spool fibres, although the process was unstable. At higher throughputs (17.28 g/min or 25.92 g/min.), Material B showed low melt strength, with filaments breaking as they left the spinneret.

In conclusion, it was not possible to obtain fibres under a stable process. At throughputs of 17.28 g/min or 25.92 g/min, that resulted in shear rates of 314 s^{-1} and 472 s^{-1} , respectively, the process resulted to be completely unstable. Improvement in spinnability was observed at the lower throughput of 8.64 g/min, where the shear rate was 157 s^{-1} , indicating that Material B is sensitive to shear rates above 314 s^{-1} . Therefore, the most promising conditions for melt spinning of Material B appeared to be a combination of the highest temperatures and lowest throughput. Figure 33 shows the different attempted spinning trials; A_Filament I was obtained as shown in image c).

Overall, Material B is not compatible with the attempted spinning parameters, particularly at higher shear rates and throughputs.

Table 42 - Material B extrusion temperature profile.

Temperature profile	Filament reference	Extruder heating zones (°C)			Melt pump (°C)	Melt temperature (°C)	Transfer line (°C)	Spinneret (°C)	Throughput (g/min)	Pressure (bar)
		1	2	3						
B_T1	Not spinnable	165	181	175	185	179	171	180	8.64	95
	Not spinnable					188			25.92	190
B_T2	B_Filament I	177	195	190	189	188	199	205	8.64	66
	Not spinnable					195			25.92	145



Figure 32 - Spinning trials: a) Low extrusion temperatures (B_T1), Low throughput; b) Low extrusion temperatures (B_T1), High throughput; c) High extrusion temperatures (B_T2), Low throughput; d) High extrusion temperatures (B_T2), High throughput.



Table 43 presents the spinning parameters of B_Filament I. Since Material B did not allow for increased spinning speeds or the application of different stretches, B_Filament I was spooled under a low CDR, resulting in a theoretical density of 864 dtex. In practice, the linear density could not be measured. **Figure 34** shows the B_Filament I obtained sample. Other parameters related to the extrusion process, calculated shear rates, torques and pressure for each trial are specified in the “Annex I - parameters related to the extrusion process”.

Table 43 - Material B spinning parameters of B_Filament I

Filament reference	Throughput (g/min)	Rolls speed (m/min)			Rolls temperature (°C)			DDR (V1/V0)	CDR (V2/V1)	Linear Density (dtex)
		R1	R2	R3	R1	R2	R3			
B_Filament I*	8.64	90	100	100	80	41	25	127.18	1.11	Not measurable

* Filament obtained under an unstable spinning process that may lack filaments and possess other defects.



Figure 33 - B_Filament I obtained from Material B.

6.2 Mechanical characterization

6.2.1 Linear density

Linear density was evaluated according to *ISO 2060: Textiles — Yarn from packages — Determination of linear density (mass per unit length)* by the skein method. Three samples from each fibre were measured.

Table 44 presents data of filaments obtained from Material A; the ones produced under stable conditions are highlighted in the Table.



Table 44 - Data of A_Filament

Filament reference	Throughput (g/min)	DDR (V1/V0)	CDR (V2/V1)	Linear Density dtex (g/10000 m)
A_Filament 1*	25.92	42.39	1.83	1300 ± 71
A_Filament 2	8.64	127.18	1.33	663 ± 21
A_Filament 3*	25.92	42.39	1.72	1579 ± 8
A_Filament 4	25.92	42.39	1.83	1448 ± 14
A_Filament 5*	25.92	42.39	2.33	1132 ± 8
A_Filament 6*	25.92	42.39	2.28	1168 ± 11
A_Filament 7*	25.92	42.39	4.22	600 ± 10
A_Filament 8	25.92	42.39	3.17	786 ± 8
A_Filament 9	34.56	31.79	3.39	986 ± 14
A_Filament 10	25.92	42.39	3.32	784 ± 19

* Filament obtained under an unstable spinning process that may lack filaments and possess other defects.

6.2.2 Tenacity and tensile properties

Mechanical tests were performed through an internal procedure based on *ASTM D 3822:07 - Standard Test Method for Tensile Properties of Single Textile Filaments*, using a universal mechanical test machine (Shimadzu AGX-V 50 kN, **Figure 14**), with a 100 N load cell. Tests were carried out 7 days after production on 10 specimens for each filament, test speed was set at 250 mm/min and gauge length at 25 mm. Elongation at break and force at break have been registered to determine the filament tenacity. **Table 45** presents mechanical characterization results for each material. Filaments obtained under stable conditions are highlighted in the table.

Table 45 - Mechanical characterization results.

Filament Reference	Linear Density dtex (g/10000 m)	Force at break (cN)		Tenacity (cN/dtex)		Elongation at break (%)	
		Av.	σ	Av.	σ	Av.	σ
A_Filament 1*	1300 ± 71	1688	55	1.30	0.04	38	4
A_Filament 2	663 ± 21	680	46	1.03	0.07	32	2
A_Filament 3*	1579 ± 8	2059	49	1.30	0.03	44	3
A_Filament 4	1448 ± 14	1663	59	1.15	0.04	35	2
A_Filament 5*	1132 ± 8	1416	60	1.25	0.05	23	1





A_Filament 6*	1168 ± 11	1409	92	1.21	0.08	26	4
A_Filament 7*	600 ± 10	1036	54	1.73	0.09	27	2
A_Filament 8	786 ± 8	998	48	0.88	0.06	35	2
A_Filament 9	986 ± 14	690	72	1.15	0.07	36	3
A_Filament 10	784 ± 19	1129	164	1.33	0.21	29	5

* Filament obtained under an unstable spinning process that may lack filaments and possess other defects.

6.3 Result discussion

Table 46 presents the parameters adjusted during the melt spinning process of Material A to produce ten different filaments, aiming to achieve the highest possible tenacity.

Table 46 - Melt spinning trial overview

Filament Reference	Parameters adjusted to increase tenacity	Stable?	Tenacity (cN/dtex)	Max. Force (cN)
A_Filament 1	CDR: 1.83	No	1.30	1688
A_Filament 2	Higher "Hot stretching "ratio (DDR)	Yes	1.03	680
A_Filament 3	Lower Extrusion temperatures	No	1.30	2059
A_Filament 4	Higher Extrusion temperatures	Yes	1.15	1663
A_Filament 5	Higher Feed Roll temperature	No	1.25	1416
A_Filament 6	DR: 2.28	No*	1.21	1409
A_Filament 7	<ul style="list-style-type: none"> Highest Feed Roll temperature (100 °C) Highest Extrusion temperatures ($T_m = 197$ °C) (Highest DR: 4.22) 	No*	1.73	1036
A_Filament 8	DR: 3.17	Yes	0.88	690
A_Filament 9	Higher Extrusion speeds (48 rpm); DR: 3.39	Yes	1.15	1129
A_Filament 10	Drawn also between R2 and R3; Total DR: 3.32	Yes	1.35	1056

*1 filament breaks periodically (after 2 minutes)

The highest obtained tenacity was 1.73 cN/dtex in A_Filament 7, produced under the highest temperature profile and feed roll (R1) temperature, allowing this material to be drawn at the highest ratio of 4.22 (CDR). However, A_Filament 7 was produced under the most unstable conditions, and one filament broke periodically during processing.



Figure 34 shows a comparison of force and break and tenacity values of all the ten obtained filaments. The filaments obtained with unstable processes have a different light green pattern of the graph columns. As observed, the second highest tenacity value is registered for A_Filament 10, obtained with a stable process. A_Filament 4 also presents a good balance between force at break and a medium value of tenacity value registered for this trial.

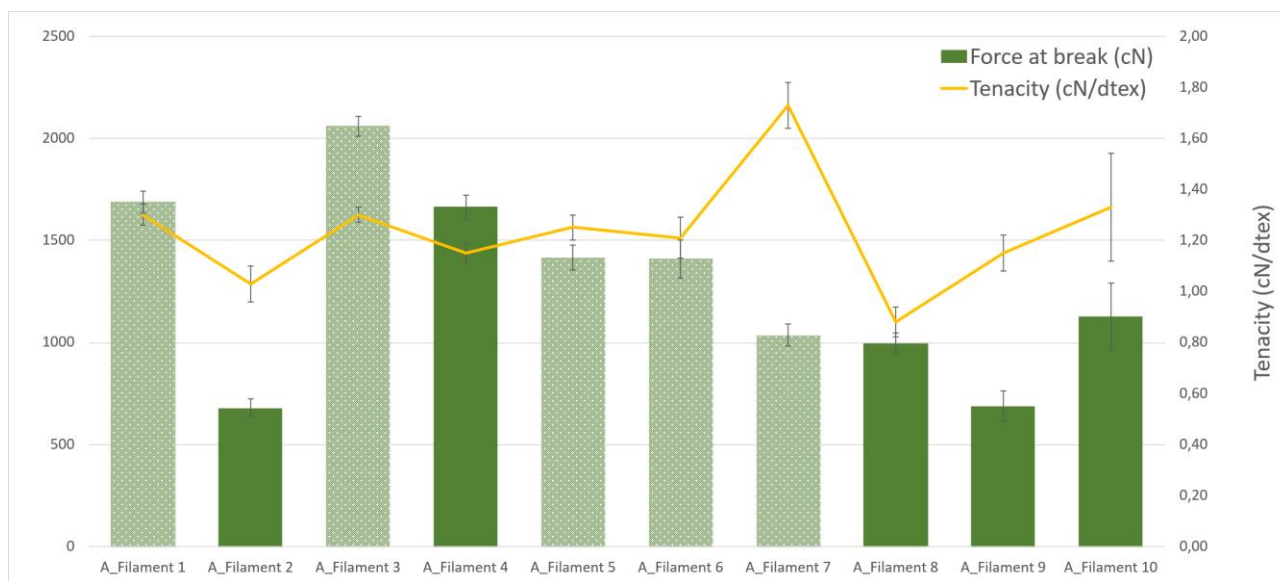


Figure 34 - Comparison of force at break and tenacity values of all the filaments obtained from Material A.

Optical microscopy was carried out to better evaluate the cause of the incompatibility of Material B to melt spinning process.

Figure 35 shows the optical microscopy images of two samples: A-Filament 2 and A_Filament 4, with a measured linear density of 663 ± 21 dtex and 1448 ± 14 dtex, respectively. The two filaments were obtained under stable processing conditions. As it can be observed from image c), the filaments appear homogeneous with a smooth surface and regular diameter.

Figure 37 shows the optical microscopy of the manually collected B_Filament 1. Unlike filaments produced with Material A, B_Filament 1 was obtained under unstable processing conditions. The image reveals defects within the filament cross-section, which appears inhomogeneous, with an irregular diameter and a rough surface. These defects may be attributed to the degradation of the additive (CNW) or to its particle size, which exceeds the filament diameter. In the image, the single filament has a diameter of $139.5 \mu\text{m}$, while the particle has a dimension of $395.1 \times 205.9 \mu\text{m}$.

These observations are even more evident in Figure 22, which shows the optical microscopy image of filament waste: the particle has a diameter of $111.7 \mu\text{m}$, whereas the filament diameters measure 33.1 and $18.7 \mu\text{m}$, respectively.

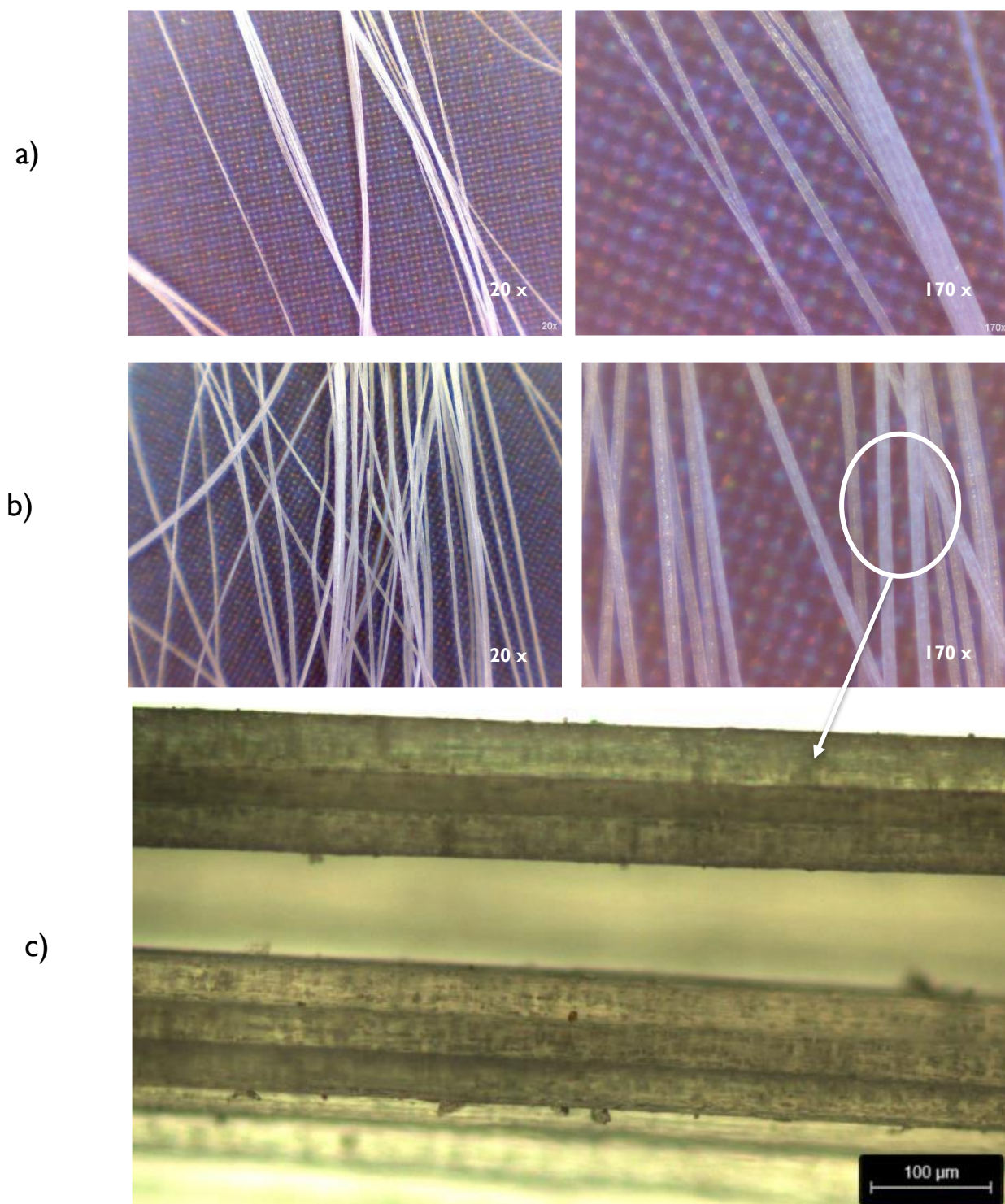


Figure 35 - Optical microscopy of Material A filaments – longitudinal images.

a) A_Filament 2, b) A_Filament 4, c) magnified detail of A_Filament 4.



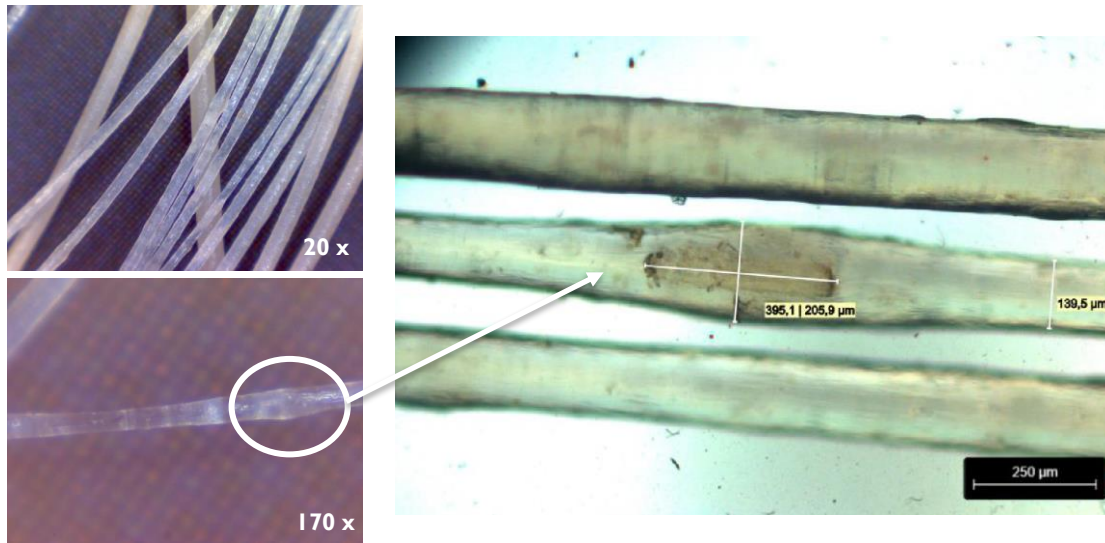


Figure 36 - Optical images of B_Filament

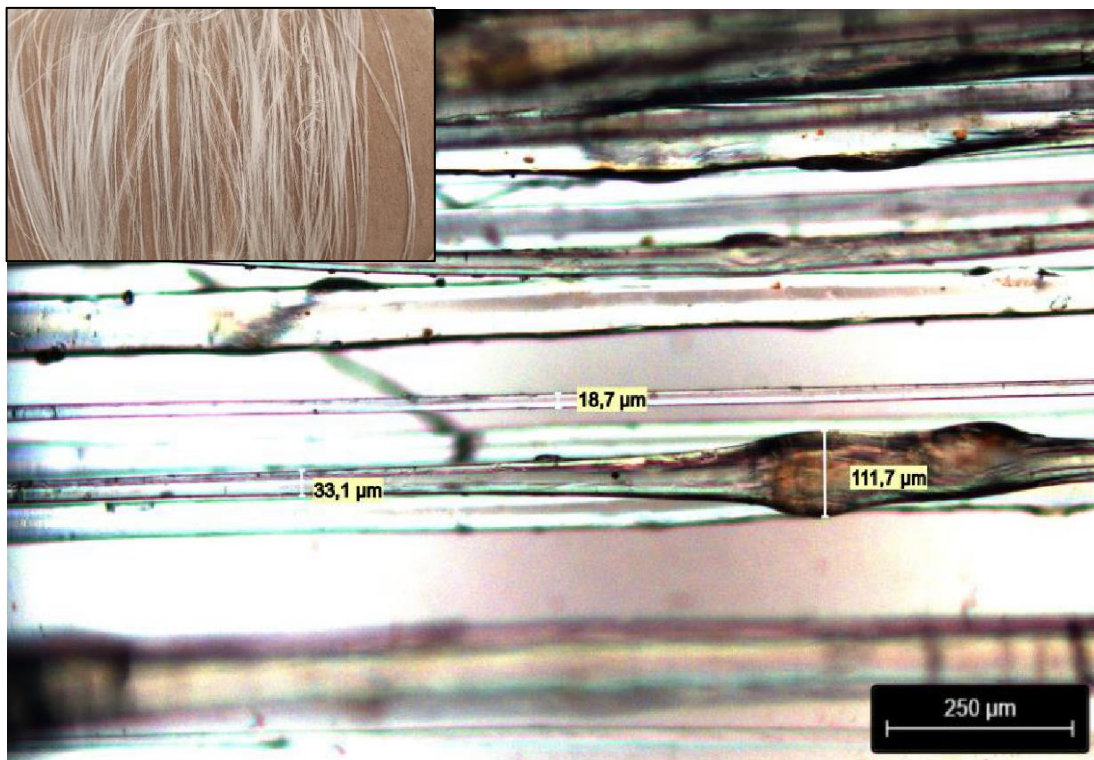


Figure 37 - Optical microscopy of Material B waste – longitudinal images.

6.4 Conclusions

Regarding extrusion flowability and stability, both Material A and Material B showed no issues. With Material A, it was possible to achieve high drawing ratios, of around 4.22, for A_Filament 7, which, although a filament breaks periodically, shows the highest obtained tenacity, 1.73 cN/dtex.

Material B resulted to be not compatible with the attempted spinning parameters. It required higher processing temperatures in comparison to Material A and exhibited low melt strength (i.e the ability to withstand hot stretched). Its performance degraded at throughputs of 14.4g/cm³ or higher, potentially due to its sensitivity to shear rates above > 314 s⁻¹. Additionally, microscopic analysis revealed points of structural fragility. The most promising conditions for melt spinning Material B seemed to be a combination of highest temperatures and slow extrusion speeds; however, these conditions were not suitable for further scale-up.

Figure 38 shows that an enhancement of force at break and tenacity values have been achieved with material A in comparison with Compound 9. PLA/PCL. In stable condition, the highest registered values of tenacity and force at break were 1.73 cN/dtex (A_Filament 10) and 1663 cN (A_Filament 10), respectively. These values represent slight improvement compared to the tenacity value of 1.05 cN/dtex registered for “9” Fibre 4 and a great 100% increase of force at break compared to the value of 860 cN registered for “9” Fibre 2, respectively.

However, these results in terms of tenacity are still significantly below the target parameters for multifilament, as outlined in **Table I**. Further improvements of the formulations are needed.

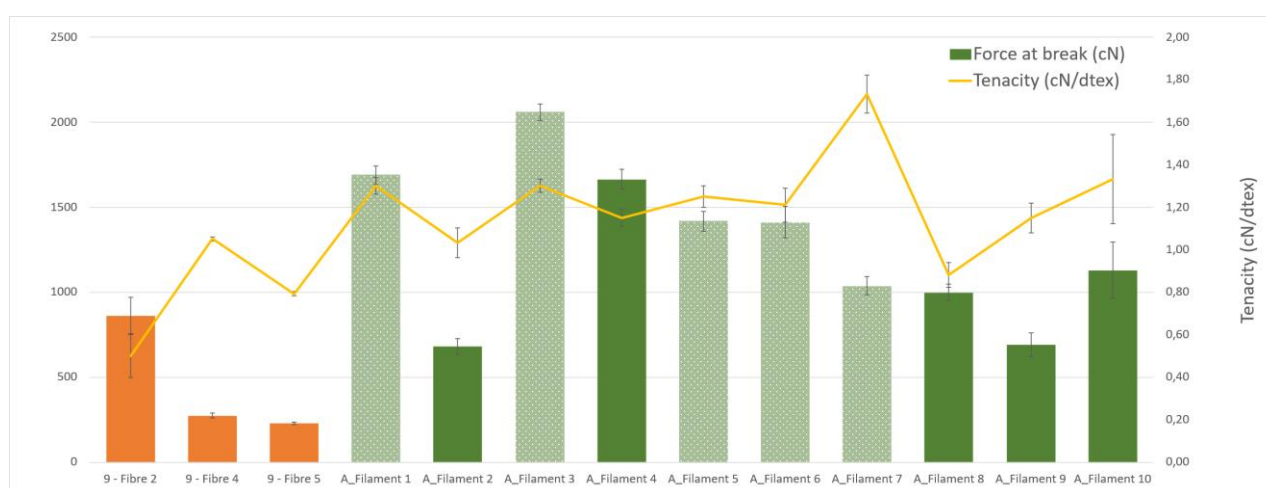


Figure 38 - Comparison of force at break and tenacity values of all the filaments obtained from Material A (green columns) and the filaments of compound 9. PLA/PCL obtained with stable processing conditions during the first phase of multifilament melt spinning trials (orange columns)

7 Blends for monofilament and multifilament production: optimization phase

For the fifth group of testing trials and based on previous tests and characterizations, Bio-Mi once again prepared four most promising formulations which should be further scaled up. Moreover, these compounds were based on Remedies 5 formulation with and without the addition of talc as well as on Remedies 6 formulation and combinations thereof.

In the focus were:

1. PBS 90: PBAT 10
2. PBS 85: PBAT 15
3. PBS 80: PBAT 20
4. PBS 80: PBAT 20 + Talc 15

Same like in previous trials, after characterization of raw materials compounding step was achieved via twin screw extrusion line and compounds were further characterized. Compounding step was successful and process was after some period stable and without difficulties. Moreover, results of characterization (thermal, rheology and physical) showed very similar results like in previous trials which is confirmation of repeatability.

Table 47 - Results of characterization of fifth group of trials

Material	T _m , °C	MFR, g / 10 min 190 °C, 2.16 kg	Density, g / cm ³	Moisture, %
PBS (90):PBAT (10)	122.6	6.1	1.243	0.277
PBS (85):PBAT (15)	119.9	5.1	1.269	0.177
PBS (80):PBAT (20)	118.4	4.3	1.264	0.200
PBS (80):PHBV (20) + TALC (15)	115.9 / 168.7	11.5	1.335	0.246

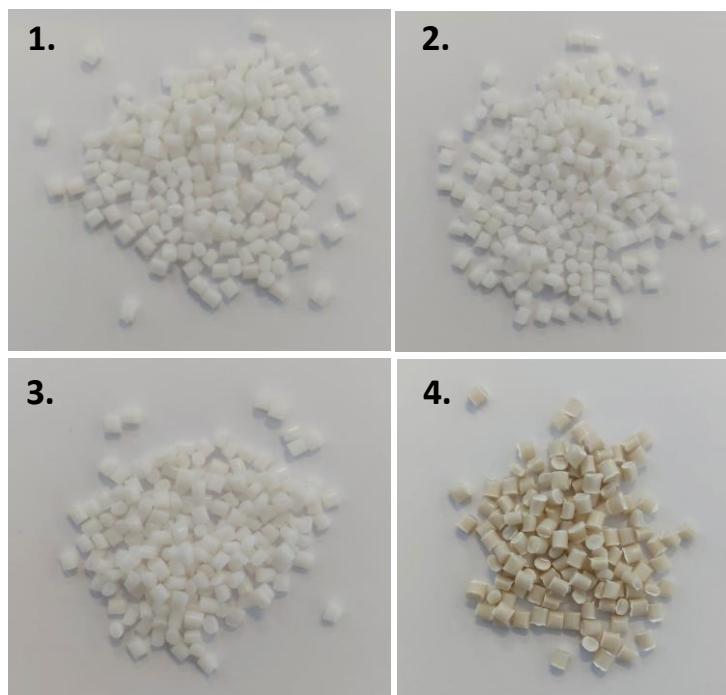


Figure 39 - Samples of obtained granulates

Final materials were sent to NTT for final validation and final decision on the most promising compounds to be scaled up.



Figure 40 - Obtained materials shipped to NTT for final validation

8 Laboratory scale multifilament production: third phase

The results of the first multifilament production phase (**Paragraph 3**) highlighted that also compound I I. PBS/PHA demonstrated promising performance in terms of process stability and tenacity value. BIOMI prepared 5 kg of a new optimized compound with an additive which could improve the tenacity of the resulting filaments:

- Material C (PBS/PHBV 80:20 + 15% Talc 15)

The sample was sent to NTT for the new spinning trial.

8.1 Spinning trials

Table 48 presents the properties of the material selected for the multifilament extrusion. Material C was dried before the tests at 65°C/16h. The moisture content was measured after the drying of each material, in a moisture analyzer (Radwag MA 50/1.X2.A.WH), which has the sensibility to measure up to 1 part per million (ppm).

The spinnability tests were carried out on a lab-scale equipment according to the steps described in **Section 3.1**.

Table 48 - Material C selected for the third phase spinnability trial and its properties.

Ref.	Material	T _m (°C)	MFR (g/10 min) [190 °C, 2.16 kg]
Material C	PBS/PHBV 80:20 + 15% Talc 15	115.9 / 168.7	11.5

Table 49 reports the temperature profile and the spinning parameters tested during the trial. Three temperature profile were tested: Low, Medium and High.

First, a medium temperature profile (T2) was tested, similar to one tested for compound I I. PBS/PHA in the first phase (**section 3.1.5**). Filaments were produced under a high throughput, due to the degradation that occurs at a low throughput, for which the exposure time to temperature is longer. This degradation was noticeable by the characteristic smell released by the compound and inability to be stretched.

At a higher temperature profile (T3), the flowability of the material at the spinneret improved, but the filaments became more fragile, and it could not withstand a low DDR.

At low temperature profile (T1), six different fibres were produced, tuning hot stretching and draw ratio parameters.

In the table different colours are used to underline the two different conditions:

- (*DDR-*, *CDR+*) to achieve the highest tenacity;
- (*DDR+*, *CDR+*) to achieve the minimum linear density.

Figure 41 shows all the obtained bobbins. Other parameters used in the production of these fibres are detailed in “Annex I - parameters related to the extrusion process”.

Table 49 - Material C temperature profile and spinning parameters of filaments.

Temperature profile	Extruder temperature profile (°C)	Spinneret (°C)	Throughput (g/min)	Hot stretching DDR (v1/v0)	Draw Ratio CDR (v2/v1)	Filament reference
T1 Low	164 - 174	160	35,24 (High)	DDR- 35	CDR+ 1.44	C_Filament 6
				DDR+ 135	CDR+ 1.23	C_Filament 5
			16,02 (Low)	DDR- 76	CDR+ 1.72	C_Filament 3*
				DDR+ 178	CDR+ 1.21	C_Filament 4
T2 Medium	180	180	35,24 (High)	DDR+ 150	CDR+ 1.21	C_Filament 1*
				DDR- 35	CDR+ 1.67	C_Filament 2*
			16,02 (Low)	Not possible	-	-
T3 High	185 – 195	210	35,24 (High)	Not possible	-	-
			16,02 (Low)	Not possible	-	-

*filament breaks periodically

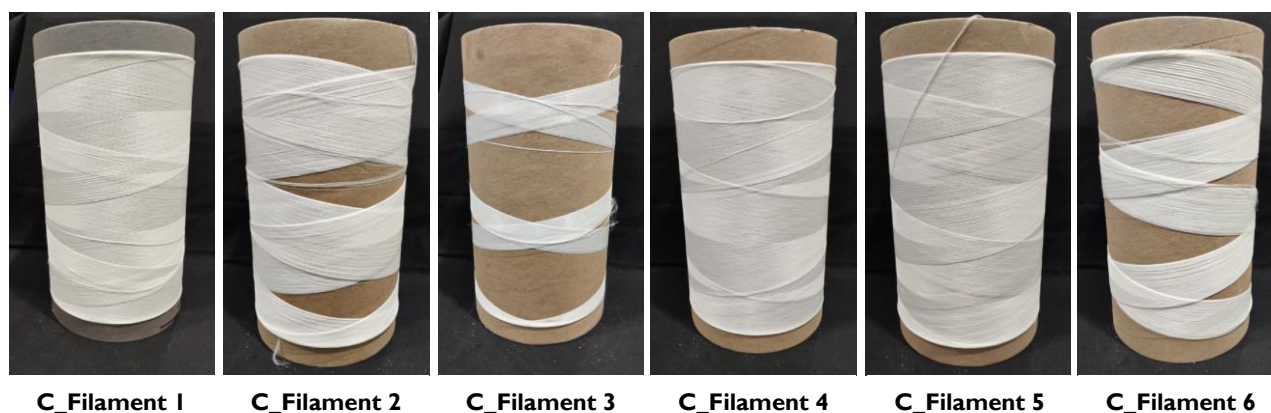


Figure 41 - Filaments obtained from Material C.

8.2 Mechanical characterization

8.2.1 Linear density, tenacity and tensile properties

Linear density was evaluated according to ISO 2060: *Textiles — Yarn from packages — Determination of linear density (mass per unit length)* by the skein method. Three samples from each fibre were measured.

Mechanical tests were performed through an internal procedure based on *ASTM D 3822:07 - Standard Test Method for Tensile Properties of Single Textile Filaments*, using a universal mechanical test machine (Shimadzu AGX-V 50 kN, **Figure 14**), with a 100 N load cell. Tests were carried out 7 days after production on 10 specimens for each filament, test speed was set at 250 mm/min and gauge length at 25 mm. Elongation at break and force at break have been registered to determine the filament tenacity.

Table 50 presents mechanical characterization results for each obtained Filament. Filaments obtained under stable conditions are highlighted in the table.

Table 50 - Linear density and mechanical tensile properties of filaments obtained from material C.

Filament Reference	Linear Density dtex (g/10000 m)	Force at break (cN)		Tenacity (cN/dtex)		Elongation at break (%)	
		Av.	σ	Av.	σ	Av.	σ
C_Filament 1*	591 ± 13	308	11	0.52	0.02	61	
C_Filament 2*	2146 ± 33	1086	64	0.51	0.03	135	
C_Filament 3*	944 ± 20	546	40	0.58	0.04	40	
C_Filament 4	560 ± 9	282	11	0.50	0.02	61	
C_Filament 5	743 ± 38	387	14	0.52	0.02	77	
C_Filament 6	2473 ± 45	1142	72	0.46	0.03	129	

* Filament obtained under an unstable spinning process that may lack filaments and possess other defects.

8.3 Discussion

Figure 43 shows a comparison of force and break and tenacity values for all six obtained filaments. The filaments produced under unstable processes are represented by a light green pattern in the graph columns.

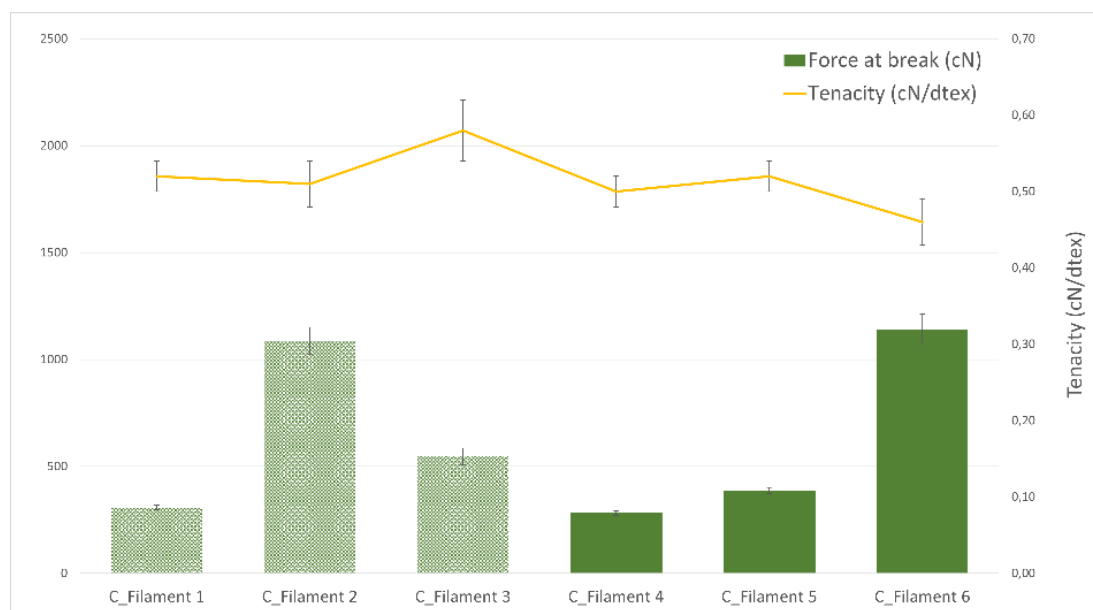


Figure 42 - Comparison of force at break and tenacity values of all the filaments obtained from Material C.

According to data in **Table 49**, C_filaments number 1, 2, 5 and 6 were produced with a high throughput (35,24 g/min) whereas C_filaments 3 and 4 with a low throughput (16,02 g/min). A lower throughput appeared to be the optimal parameter to achieve higher tenacity value: the highest was recorded for C_Filament 3 (0.58 cN/dtex). This also corresponds to the highest applied draw ratio (1,72). However, C_Filament 3 was obtained under unstable processing conditions.

Despite the observed variations, tenacity values are within a relatively narrow range, 0.46 - 0.58 cN/dtex.

Considering the balance between tenacity and force at break, C_Filament 6 emerged as the best result in this trial. However, both its tenacity (0.46 cN/dtex) and elongation at break (129%) values, are significantly below the target parameters for multifilament, as outlined in **Table 1**.

8.4 Conclusions

Figure 43 shows a comparison of force and break and tenacity values of all the filaments obtained from Material C and the filaments of compound I I. PBS/PHA (first phase of multifilament production trials, **section 3.1.5**) obtained with stable processing conditions. The filaments of Material C produced under unstable processes are represented by a light green pattern in the graph columns.



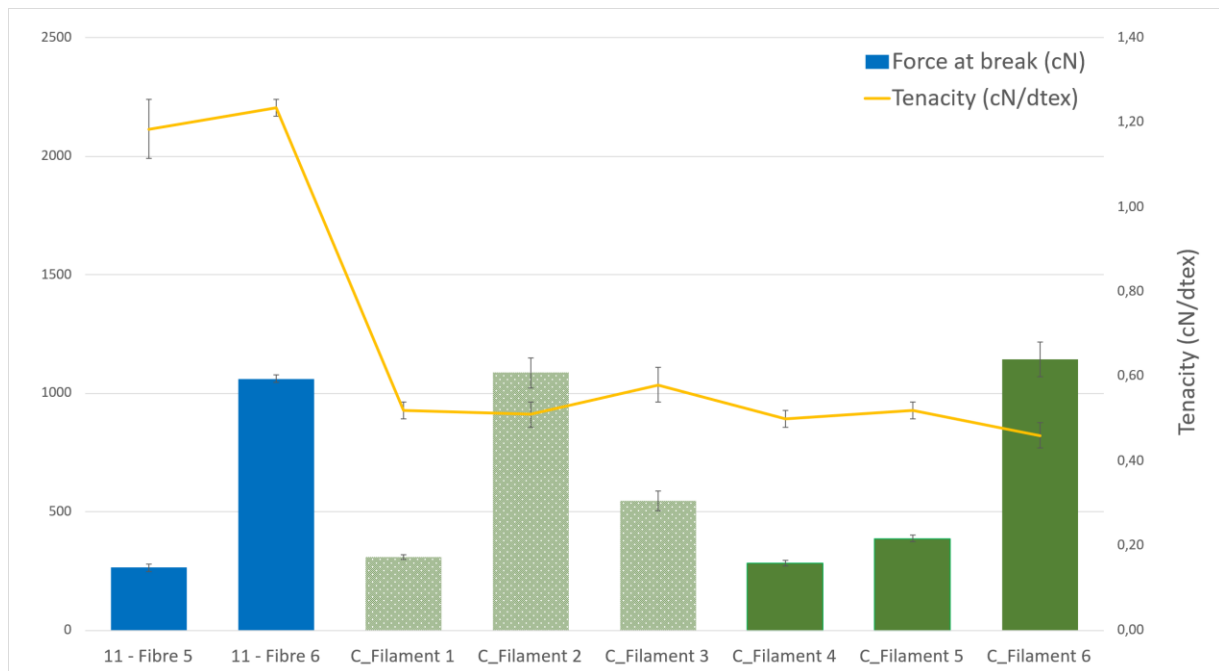


Figure 43 - Comparison of force at break and tenacity values of all the filaments obtained from Material C (green columns) and the filaments of compound 11. PBS/PHA (blue columns) obtained with stable processing conditions during the first phase of multifilament melt spinning trials.

In general, independently of the applied temperature profile and extrusion speed (throughput), the values of tenacity obtained for Material C are all similar and significantly below the values obtained by compound 11. PBS/PHA. The low tenacity values are directly related to the fact that Material C could not be further stretched, resulting in a maximum draw ratio of 1.72. 11 - Fibre 6 reached a draw ratio of 2.50 (Table 14).



9 Laboratory scale monofilament production: second phase

Considering all the experimental results, the highest tenacity values were achieved with monofilament trials. Specifically, compound 2. PBS/PBAT exhibited a tenacity of 3.15 cN/dtex, recorded for “2” Filament 1, obtained under stable processing conditions (Chapter 4). The corresponding force at break (40.4 N), according to CIT requirements, is comparable to conventional fossil-based materials used in net production. However, a notable drawback is the high elongation at break (149%). To optimize the final mechanical properties, particularly to enhance tenacity, an increase in PBS content could be explored as a potential strategy for tuning material deformation behaviour.

BIO-MI prepared 5 kg each of three new formulations to be sent to NTT for spinning trials:

- Compound C 2.1 (PBS/PBAT 90:10)
- Compound C 2.2 (PBS/PBAT 85:15)
- Compound C 2.3 (PBS/PBAT 80:20)

In addition to target parameters of Table I, filament diameter target is set between 200 and 350 μm .

9.1 Spinning trials

Table 50 provides the selected compound properties. Prior processing, materials were dried for 24h at 60°C.

Table 51 - Compounds selected for spinnability trials and their properties.

Ref	Material	T _m (°C)	MFR (g/10 min) 190 °C, 2.16 kg
C 2.1	PBS/PBAT 90:10	122,6	6.1
C 2.2	PBS/PBAT 85:15	119,9	5.1
C 2.3	PBS/PBAT 80:20	118,4	4.3

The extrusion trials were carried out on lab-scale equipment as described in section 4.1, following the defined steps. The Total Draw Ratio (TDR) is calculated as the product of the individual draw ratios at each stage (DR1*DR2).

At the temperature of 120 °C, all the material showed a moisture content of zero.

The trial started with the processing of compound C 2.1, under the similar conditions applied compound 2. PBS/PBAT from the first trial (section 4.1.1):

- Extrusion temperature profile: 170 - 180 °C

- Oven I temperature: 125 °C
- Total Draw Ratio: 6,7

These processing conditions resulted in an unstable process. Moreover, a characteristic smell occurs, indicating the material degradation at these temperatures. To stabilize the process, the following steps were applied, as shown in **Figure 27**. As a result, once reached stable processing condition, Filament C 2.1_01 was collected.

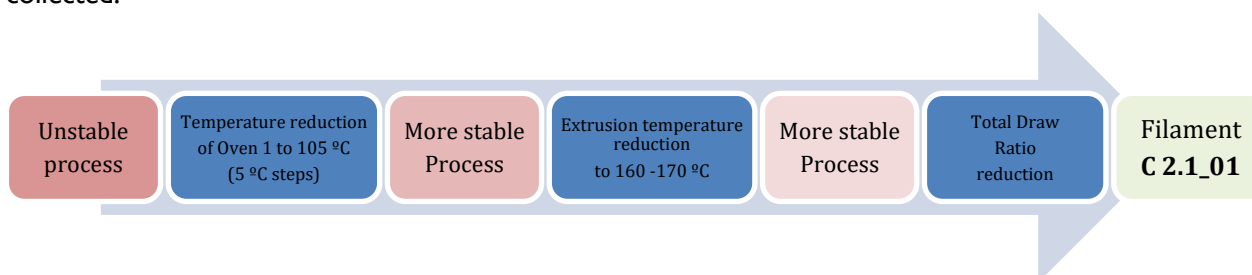


Figure 44 - Steps for extrusion parameter optimization to achieve stable processing conditions.

Table 52 presents the extrusion temperature profile set for the processing of all the three compounds. During trials, multiple diameter measurements were taken along the length of the filaments using a micrometer. The drawing parameters are listed in **Table 21**.

Table 52 - Extrusion temperature profile of filaments obtained from the three compounds.

Temperature profile	Filament reference	Extruder heating zones (°C)			Die (°C)	Oven #1	Oven #2
		1	2	3			
Medium	C 2.1_01	160	165	170	170	105	55
Low 1	C 2.1_02	120	125	125	130	95	45
Low 1	C 2.2_01	120	125	125	130	95	45
Low 1	C 2.2_02	120	125	125	130	95	45
Low 2	C 2.2_03	125	130	135	135	95	45
Low 1	C 2.3_01	120	125	125	130	95	45

Table 53 - Drawing parameters filaments obtained from the three compounds.

Ref	Rolls speed (m/min)			Draw ratio #1 (R2/R1)	Draw ratio #2 (R3/R2)	Total Draw ratio (DR1*DR2)	Max. Velocity (m/min)	Filament diameter (µm)
	Roll stand #1 (R1)	Roll stand #2 (R2)	Roll stand #3 (R3)					
C 2.1_01	5.2	15	20	2.88	1.33	3.85	20.0	467.10 ± 5.72



C 2.1_02	5.2	27.3	28.2	5.25	1.03	5.42	28.2	330.70 ± 8.08
C 2.2_01	5.2	27.3	28.2	5.25	1.03	5.42	28.2	349.00 ± 24.61
C 2.2_02	6	7.5	34.7	1.25	4.63	5.78	34.7	360.90 ± 10.61
C 2.2_03	5.2	27.3	28.2	5.25	1.03	5.42	28.2	326.00 ± 4.98
C 2.3_01	5.2	27.3	28.2	5.25	1.03	5.42	28.2	353.40 ± 17.14

Stable processing conditions for compound C 2.1 were reached at first with a medium temperature profile. However, the resulting diameter of filament C 2.1_01 resulted to be 467 µm, exceeding the target value, due to the degradation occurring under this temperature profile that did not allow it to be further stretched. Then, with a lower temperature profile (Low I), it was possible to produce filament C 2.1_02, which diameter (330.70 µm) is compliant with the target requirements.

Extruding and stretching the C 2.2 under the same conditions of C 2.1_02 resulted in filament C 2.2_01, obtained under stable conditions. Filaments C 2.2_02 and C 2.2_03 were produced under different conditions as attempts to increase the tenacity: higher total draw ratio or higher temperature profile. Filament C 2.3_01 was produced under the same conditions of C 2.2_01, with the maximum possible Total Draw Ratio for the material.

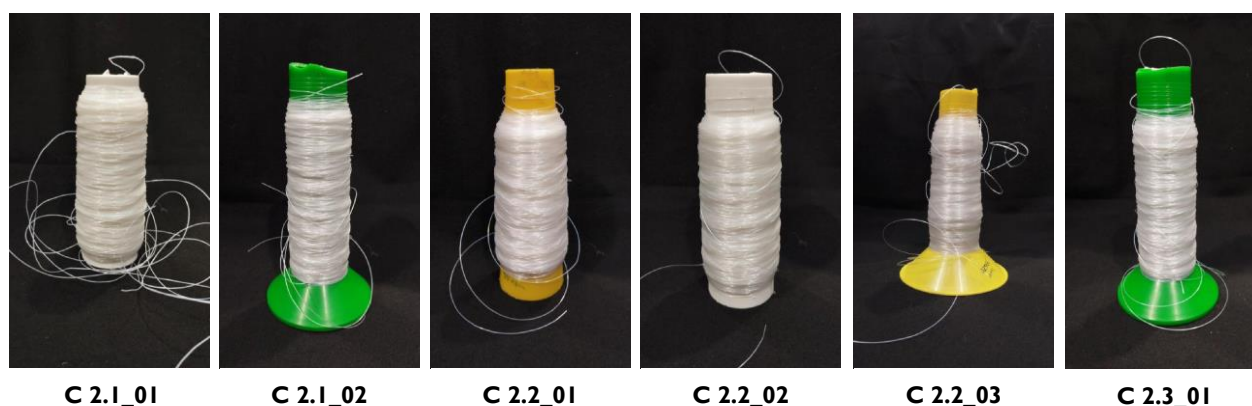


Figure 45 - Filaments obtained from compounds C 2.1, C 2.2, C2.3.

9.2 Mechanical characterization

Linear density was evaluated according to *ISO 2060: Textiles — Yarn from packages — Determination of linear density (mass per unit length)* by the skein method. Three samples from each filament were measured. Mechanical tests were performed according to *ASTM D 3822:07 - Standard Test Method for Tensile Properties of Single Textile Filaments*, using a universal mechanical test machine (Shimadzu AGX-V 50 kN, **Figure 14**), with a 100 N load cell. Tests were carried out 7 days after production on 10 specimens for each



multifilament, test speed was set at 250 mm/min and gauge length at 25 mm. Elongation at break and force at break have been registered to determine the filament tenacity.

Table 54 presents mechanical characterization results for each material, including linear density values.

Table 54 - Mechanical characterization results and linear density values.

Ref	Filament diameter (μm)	Linear Density (dtex)	Force at break (N)		Tenacity (cN/dtex)		Elongation at break (%)	
			Av.	σ	Av.	σ	Av.	σ
C 2.1_01	467.10 ± 5.72	2241 ± 10	32.07	70.27	1.43	0.15	228	20
C 2.1_02	330.70 ± 8.08	1335 ± 6	34.20	43.24	2.56	0.07	101	12
C 2.2_01	349.00 ± 24.61	1316 ± 14	34.76	48.65	2.64	0.07	98	7
C 2.2_02	360.90 ± 10.61	1325 ± 11	31.27	14.86	2.36	0.07	113	5
C 2.2_03	326.00 ± 4.98	1625 ± 14	38.70	8.11	2.37	0.03	93	6
C 2.3_01	353.40 ± 17.14	1379 ± 8	36.27	28.38	2.63	0.03	100	9

9.3 Discussion

Figure 46 shows the comparison of mechanical properties of monofilaments obtained from the tested compounds.

Monofilament C 2.1_01 was the first to be produced under stable processing condition using a medium temperature profile. However, as it can be observed in the graph, its mechanical performance did not meet the target requirements, exhibiting low tenacity, excessively high elongation at break, and an inadequate diameter.

After optimizing the processing conditions with lower temperature profiles and higher total draw ratio, all subsequently produced monofilaments from compound C 2.1, C 2.2 and C 2.3 showed increased tenacity values and significantly reduced elongation at break. Although tenacity values remained within a narrow range (2.36 - 2.64 cN/dtex), the highest value was recorded for monofilament C 2.2_01. Further adjustments to the processing conditions (filaments C 2.2_02 and C 2.2_03) did not result in a further increase in tenacity. Filament C2.3_01, produced under the same conditions of C 2.2_01, exhibited a comparable tenacity value of 2.63 cN/dtex.

Similarly, the force at break and elongation at break values exhibited a consistent trend across the samples, ranging from 31.27 to 38.70 N and 113% to 93%, respectively.

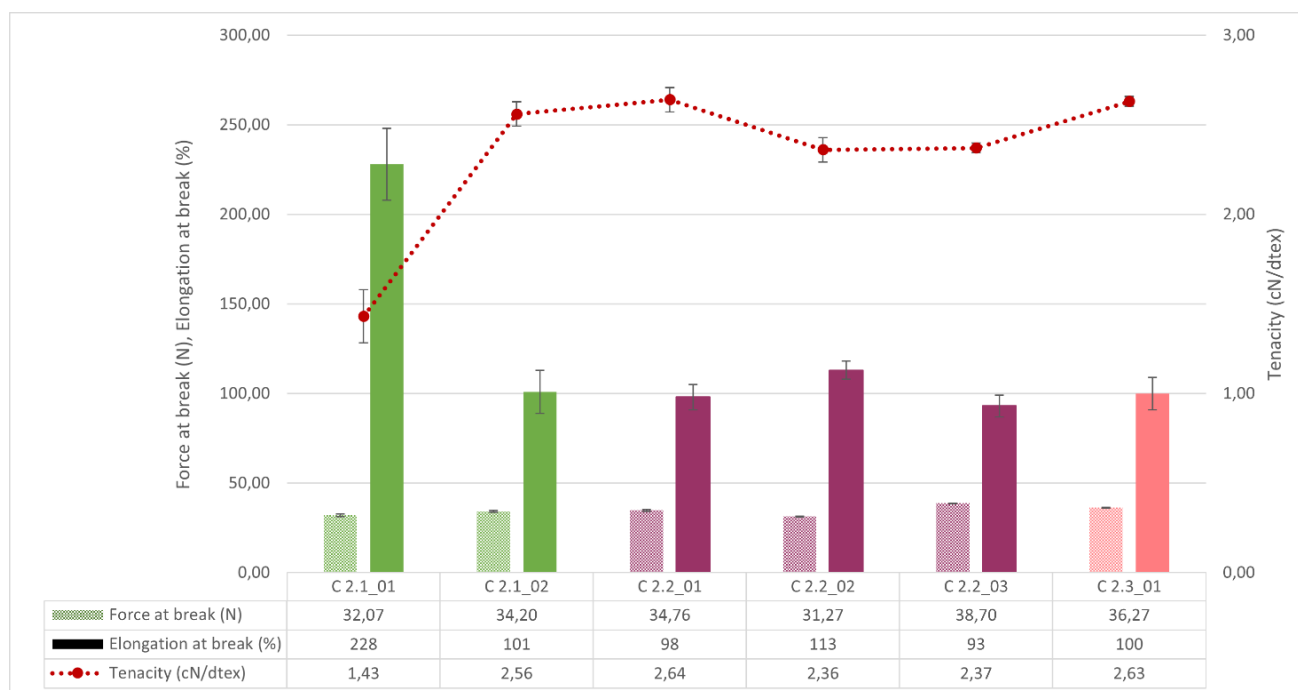


Figure 46 - Comparison of force at break, elongation at break and tenacity values between all the monofilaments obtained from compounds C 2.1, C 2.2, C2.3.

9.4 Conclusions

The three compounds presented a suitable behaviour under the monofilament extrusion process. Comparing to processing conditions of compound 2. PBS/PBAT, from the previous phase of trials, there was the need to decrease the working temperatures, due to noticeable degradation of compound C2.1. Furthermore, comparing compound 2. PBS/PBAT, the new compounds (C2.1, C2.2 and C2.3) exhibited a reduced stretchability, that resulted in lower overall values of tenacity, as observed in Figure 47. When compared to the results of compound 2. PBS/PBAT, the elongation at break values of compounds C2.1, C2.2 and C2.3 resulted lower. However, these values remain above the target monofilament specifications outlined in Table I.



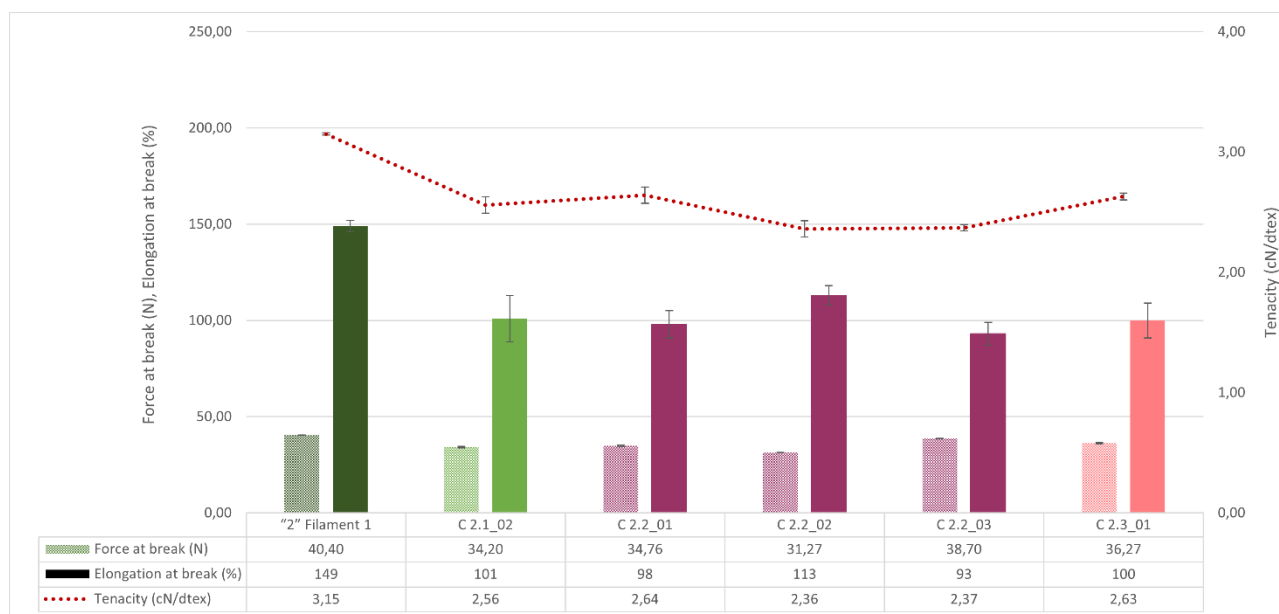


Figure 47 - Comparison of force at break, elongation at break and tenacity values between monofilaments obtained from compounds C 2.1, C 2.2, C2.3 and the monofilament obtained from compound 2. PBS/PBAT.

The three compounds were also analysed and characterised by the internal textile Laboratory of CIT, in order to compare the results obtained with its standard test procedure with the ones made by NTT. Below there are the data obtained by CIT compared to the NTT data for each sample:

Table 55 - Test comparison between NTT and CIT data

PBS:PBAT (90:10)	Linear Density dtex	Breaking Force N	Elongation at break %	Tenacity cN_dtex
Compound 2.1_01	2241	32,07	228	1,43
Our test AF145/24	2285	32,96	135,42	1,441
Difference vs NTT data:	1,96%	2,78%	-40,61%	0,77%
PBS:PBAT (90:10)	Linear Density dtex	Breaking Force N	Elongation at break %	Tenacity cN_dtex
Compound 2.1_02	1335	34,2	101	2,56
Our test AF146/24	1330	34,92	38,41	2,627
Difference vs NTT data:	-0,37%	2,11%	-61,97%	2,62%





PBS:PBAT (80:20)	Linear Density dtex	Breaking Force N	Elongation at break %	Tenacity cN_dtex
Compound 2.3_01	1379	36,27	100	2,63
Our test AF150/24	1395	37,08	33,52	2,661
Difference vs NTT data:	1,16%	2,23%	-66,48%	1,18%

PBS:PBAT (85:15)	Linear Density dtex	Breaking Force N	Elongation at break %	Tenacity cN_dtex
Compound 2.2_01	1316	34,76	98	2,64
Our test AF147/24	1335	36,88	41,32	2,764
Difference vs NTT data:	1,44%	6,10%	-57,84%	4,70%

PBS:PBAT (85:15)	Linear Density dtex	Breaking Force N	Elongation at break %	Tenacity cN_dtex
Compound 2.2_02	1325	31,27	113	2,36
Our test AF148/24	1345	31,88	51,23	2,37
Difference vs NTT data:	1,51%	1,95%	-54,66%	0,42%

PBS:PBAT (85:15)	Linear Density dtex	Breaking Force N	Elongation at break %	Tenacity cN_dtex
Compound 2.2_03	1635	38,7	93	2,37
Our test AF149/24	1645	41,2	40,85	2,504
Difference vs NTT data:	0,61%	6,46%	-56,08%	5,65%

The results obtained were almost comparable, except for the difference in elongation at break which resulted in 40-66% lower values in the CIT test. This was probably due to the different test conditions or the aging of the material. The lower elongation at break values were good news for the industrial partner CIT because they were more similar to the standard fossil-based raw material and this range is more suitable for loom production of the nets.



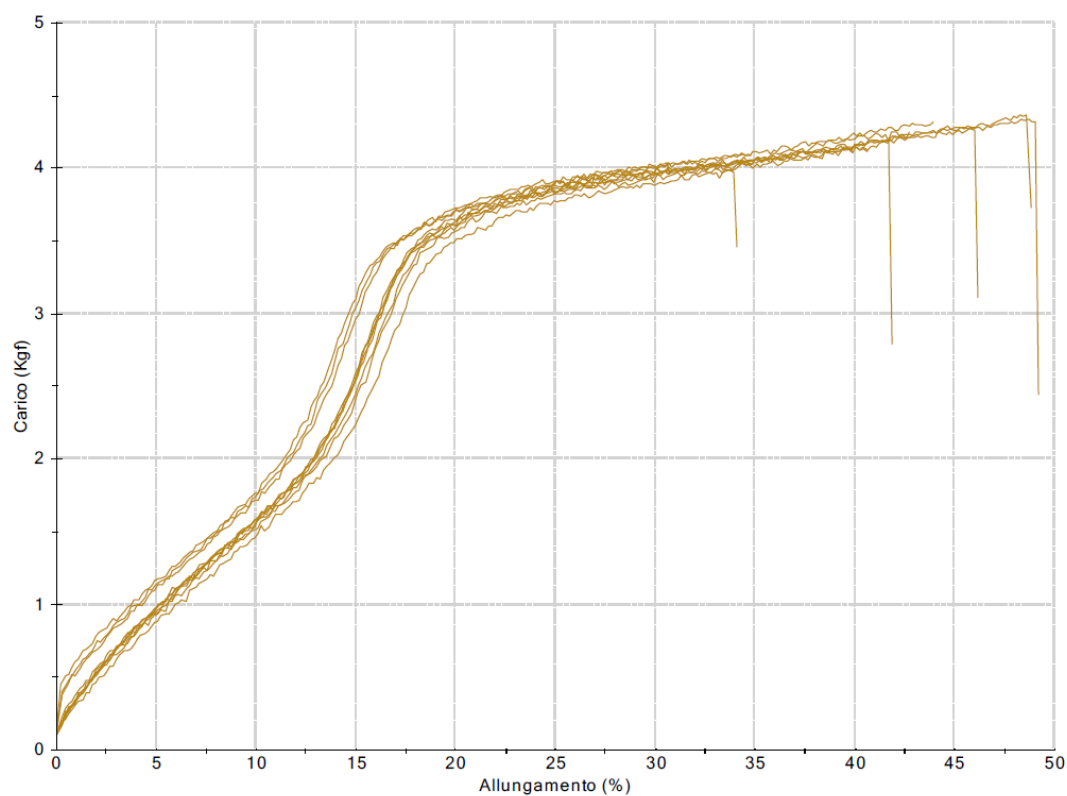


Figure 48 - Diagram Force – Elongation of Sample 2.2_03

After the analysis of the test and the diagram force-elongation of each sample, the yarn **sample 2.2_03** was selected for the industrial spinning scale-up because of the slighter higher breaking force, even if the tenacity is a little lower than sample 2.2_01



10 C 2.2 compound production for scale-up

After longer characterization and processing trials all partners together decided to go with scaling up of compound which was based on PBS 85:PBAT 15 without fillers or fibers. For scaling up trials Bio-Mi used same equipment but with higher feeding and production rates. For this purpose, BioMi used twin screw extrusion line with screw diameter of 35mm, L/D ratio of 44:1, with vacuum and atmospheric degassing and side feeders. Moreover, strands were cooled in water bath and further were dried and pelletized into granulates. After characterization of raw materials, Bio-Mi started with compounding step and further, as usual granulates were characterized.



Figure 49 - Compounding during scaling up trial



Figure 50 - Processing and control parameters during compounding step

Table 56 - Results of characterization of first scaling up trials

Parameter	PBS	PBAT	PBS 85/PBAT 15
$T_m, ^\circ\text{C}$	126.3	136.0	129.3
MFR, g/10 min 190 $^\circ\text{C}$, 2.16 kg	5.5	5.0	3.5 – 4.5
Density, g/cm ³	1.242	1.210	1.241
Moisture, %	0.162	0.180	0.137

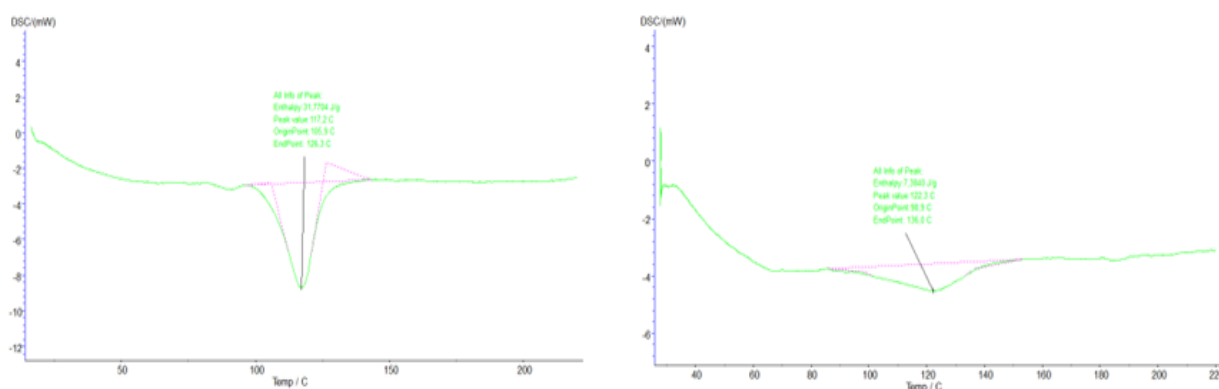


Figure 51 - Thermal characterization of raw materials PBS (left) and PBAT (right) 1st heating curve

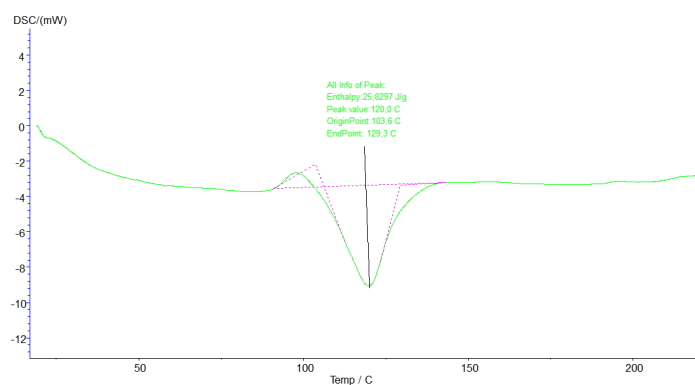


Figure 52 - Thermal characterization of PBS:PBAT compound, 1st heating curve



Compounding step was very successful and granulates have very good quality. After drying for four hours at 40°C, 300kg of compounds were shipped to NTT for further processing. During scaling up there were no problems except at the beginning of processing due to scaling up and changing of processing parameters.



Figure 53 – The pallet with 300kg of compounds shipped to NTT



II Scale-up of monofilament production

BIOMI produced 300 kg of compound C 2.2 and send it to NTT (Figure 54).

The material was sent to NTT's partner for the production of the monofilament, with the objective of industrially replicate C 2.2_03 filament obtained in an optimization scale with the following target processing conditions and properties:

- Extrusion temperatures: Between 125-135 °C;
- Filament diameter: $326 \pm 4,98 \mu\text{m}$ ($< 350 \mu\text{m}$);
- Linear density: $1635 \pm 14 \text{ dtex}$ or lower;
- Tenacity: 2.37 cN/dtex or higher.

According to the request of CIT, the filament spooling request was:

- 100 “DIN 200” spools, with between 1 to 1.5 kg per spool
- 210 “DIN 160” spools, with 0.5 kg per spool



Figure 54 - The 300 kg pallet of Compound C 2.2 in NTT's laboratory.

II.1 Spinning phase

The monofilament spinning was carried out using an industrial equipment with the following setup:

1. Single screw extruder
 - i. Two melt pumps: 20 cc/rot. each
 - ii. Two 90-degree extrusion heads, with 25 filaments each, 1.1 mm diameter die attached (Figure 56a)
2. A cooling water bath (Figure 56b)
3. 4 stretching stands with 7/8 rolls each and 3 heated chambers (for stretching and stabilization) (Figure 56c)
 - i. 1st godet unit

- ii. 1st stretching zone
 - iii. 2nd godet unit
 - iv. 2nd stretching zone
 - v. 3rd godet unit
 - vi. Stabilization zone
 - vii. 4th godet unit
4. Monitoring unit for diameter control (Figure 56d)
 5. Winder (Figure 56e)

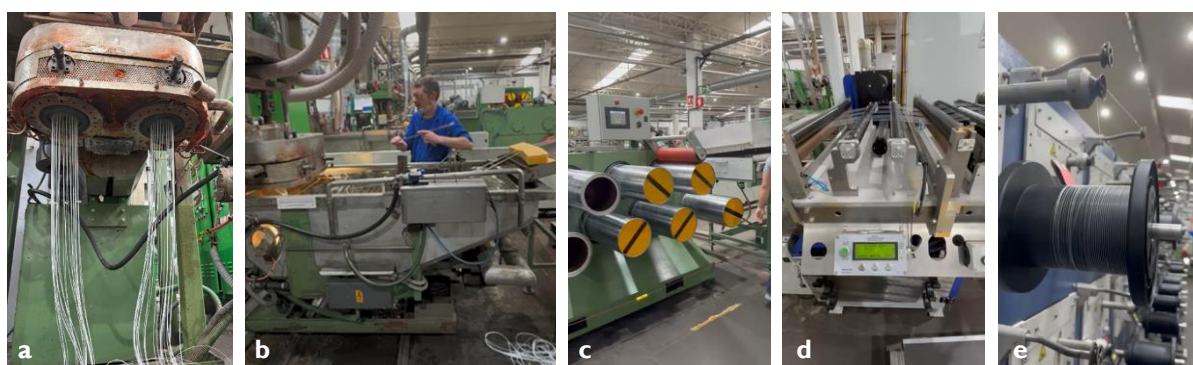


Figure 55 - Monofilament industrial equipment: different zones: a) extrusion heads, b) cooling water bath, c) stretching and stabilization, d) monitor unit, e) winder

11.1.1 Starting conditions

The material was dried at 60°C for 24 h. The starting conditions for the processing were set similarly to the ones used on the laboratorial scale optimization (section 9.1), but with higher throughputs as reported in Table 57.

Table 57 - Starting processing parameters.

Extruder		Melt pumps			Water Bath (°C)	Stretching and stabilization temperatures (°C)			Total Draw Ratio
Temperature (°C)	Velocity (rpm)	Temperature (°C)	Pressure (bar)	Throughput (kg/h)		1st zone	2nd zone	Stabilization zone	
130 - 135	21	135	139 - 140	31.98	40	95	95	60	5

No issues were observed during the extrusion stage. The material remained stable throughout the entire process, and the operational parameters of the extruder were maintained consistently.

However, significant challenges were encountered in the downstream processing stages, particularly during filament stretching operations. The process instability was most evident under a TDR of 5 condition, specifically several filaments broke during the stretching stages, suggesting that insufficient temperature might

have been a contributing factor. A low temperature could have compromised the material plasticity, making it more brittle and susceptible to breakage under tension.

The heating mechanism used in industrial system does not directly correlate with that of the laboratory unit, due to the higher number of stretching zones, necessitating specific optimization for this equipment. The inadequate thermal conditions likely contributed to process instability.

To enhance process stability and reduce filament breakages, the following optimization strategies were implemented:

- Increasing the temperatures at different stretching stages to ensure better material plasticity;
- Gradually decrease of the drawing ratios between successive stretching stages to distribute mechanical stress more evenly and prevent localized overloads that could lead to premature breakages.

Following the implementation of these optimizations, it was possible to achieve a TDR of 3 condition, corresponding to “CONDITION (SET) VI” setup, resulting in improved operational stability.

11.1.2 CONDITION (SET) VI

After optimizing the initial processing conditions, filaments produced under *CONDITION (SET) VI* were collected as follows:

- 24 bobbins DIN 160 of 0.5 kg each
- 18 bobbins DIN 200 of 0.5 kg each

using the processing parameters outlined in [Table 41](#) and [Table 42](#). As observed, the primary modifications from the initial conditions pertained to the stretching and stabilization zones.

The in-line diameter measurements confirmed that the filaments remained within the target specifications. However, after collecting multiple bobbins, periodic filament breakages were observed, accompanied by fluctuations in the material's stretching behaviour over time. Additionally, the mechanical properties measured immediately after production were lower than expected ([section 11.2](#)).

Considering these factors, an additional stage of process optimization was implemented to further improve stability and performance.

Table 58 - Processing parameters of CONDITION (SET) VI: upstream zones.

Extruder		Melt pumps			Water Bath (°C)
Temperature (°C)	Velocity (rpm)	Temperature (°C)	Pressure (bar)	Throughput (kg/h)	
130 - 135	21	135	139 - 140	31.98	40

Table 59 - Processing parameters of CONDITION (SET) VI: downstream zones.

1 st godet unit	1 st Stretching zone	2 nd godet unit	2 nd Stretching zone	3 rd godet unit	Stabilization zone	4 th godet unit	Total Draw Ratio	Diameter Monitorin g
29 m/min	100 °C	78.7 m/min	100 °C	87 m/min	70 °C	78.3 m/min	3	329 ± 10 μm

11.1.3 CONDITION (SET) V 2-6

Second phase of optimization took place according to the following parameter tuning:

- Increase of extruder velocity and melt pump throughput;
- Decrease of cooling water bath temperature;
- Decrease of the velocity of 1st godet unit.

The oven temperatures were optimized, and the stabilization stage were used as a stretching zone.

In these conditions a stable process was achieved with a TDR higher than 4 times. Monofilaments produced under *CONDITION (SET) V 2-6* were collected as follows:

- 105 bobbins DIN 160 of 0.2 kg each
- 24 bobbins DIN 200 of 1 kg each were collected.

Figure 57 shows examples of collected spools.

Table 60 - Processing parameters of CONDITION (SET) V 2-6: upstream zones.

Extruder		Melt pumps			Water Bath (°C)
Temperature (°C)	Velocity (rpm)	Temperature (°C)	Pressure (bar)	Throughput (kg/h)	
130 - 135	23	135	139 - 140	33.96	30

Table 61 - Processing parameters of CONDITION (SET) V 2-6: downstream zones.

1 st godet unit	1 st Stretching zone	2 nd godet unit	2 nd Stretching zone	3 rd godet unit	Stabilization zone	4 th godet unit	Total Draw Ratio	Diameter Monitoring
19 m/min	95 °C	74 m/min	125 °C	77 m/min	95 °C	78.3 m/min	> 4	340 ± 3 µm



Figure 56 - Examples of collected spools

11.1.4 Spinning main difficulties

During the industrial scale processing, the material behaviour in stretching phases deviated significantly from laboratory conditions, preventing the achievement of a draw ratio of 5, which was successfully obtained in lab trials. This discrepancy had a direct impact on the mechanical properties, as the lower stretch ratio influenced tenacity. One of the primary challenges encountered was time-dependent variability, likely caused by different number and set-up of blending zones, which led to fluctuations in the drawing mechanism over time. Additionally, the high inertia of industrial machinery posed a limitation, making temperature and speed adjustments slow and difficult to fine-tune, further affecting process stability. To optimize the process, approximately seven hours were dedicated to fine-tuning parameters, yet the maximum achievable draw ratio remained around 4.

These difficulties led to a considerable amount of material waste (Figure 58). Frequent filament breakages due to unstable stretching conditions caused significant interruptions, making it difficult to maintain a continuous and efficient process. Additionally, the numerous adjustments required to optimize temperature, speed, and stretching parameters were made while the process was running, leading to periods of inconsistent production where material had to be discarded. The combination of these factors resulted in increased waste, both in terms of lost material and time inefficiencies.



Figure 57 - Difficulties and optimization during processing (left) and waste produced due to the main encountered difficulties (right).

Despite these challenges, there remains potential for further improvements in both the stretch ratio and mechanical performance with additional processing time and material trials. However, the primary focus of the operation was to collect material, even if it was not produced under ideal stretching conditions. Future efforts could explore enhanced process control strategies to mitigate variability and improve the efficiency of stretching at an industrial scale.

11.2 Linear density and mechanical characterization

Linear density was evaluated according to *ISO 2060: Textiles — Yarn from packages — Determination of linear density (mass per unit length)* by the skein method. Three samples from each filament were measured. Mechanical tests were performed according to *ASTM D 3822:07 - Standard Test Method for Tensile Properties of Single Textile Filaments*.

First mechanical characterization of produced monofilaments was carried out after the production, using a universal mechanical test machine, with a 100 N load cell. Tests were carried out on 10 specimens for each multifilament, test speed was set at 500 mm/min and gauge length at 500 mm. Elongation at break and force at break have been registered to determine the filament tenacity.

Table 62 presents a comparison of the mechanical properties and linear density of monofilaments produced under two different processing conditions. While the elongation at break values are comparable, the filaments produced under Condition (Set) V2-6 exhibit superior mechanical performance, with higher force at break and tenacity. These results, obtained during the production phase, support the decision to optimize the processing conditions to achieve the performance characteristics of Condition (Set) V2-6.

Table 62 - Linear density values and tensile properties of bobbins obtained under the two processing conditions.

Filament Reference	TDR	Filament diameter (µm)	Elongation at break (%)	Force at Break (cN)	Tenacity (cN/dtex)	Linear Density (dtex)
Condition (Set) V1	3	329.00 ± 0.10	86.5 ± 3.0	1960 ± 71	1.70 ± 0.10	1153
Condition (Set) V2-6	4,12	340.00 ± 0.03	87.2 ± 2.0	3230 ± 46	2.42 ± 0.03	1336

Second mechanical characterization of *Condition (Set) V2-6* monofilaments was carried out 7 days after the production, following the test conditions of previous optimization trials, in order to compare the results obtained in laboratory scale.

Tests were carried out using a universal mechanical test machine, with a 100 N load cell. 10 specimens for each multifilament were tested, test speed was set at 250 mm/min and gauge length at 25 mm. Elongation at break and force at break have been registered to determine the filament tenacity.

Table 63 - Linear density values and tensile properties of Condition (Set) V2-6 monofilaments as a result of two different characterization phase

Filament Reference	Test condition	Elongation at break (%)	Force at Break (cN)	Tenacity (cN/dtex)	Linear Density (dtex)
Condition (Set) V2-6	1	87.2 ± 2.0	3230 ± 46	2.42 ± 0.03	1336
Condition (Set) V2-6	2	155 ± 17	2827 ± 97	2,09 ± 0,07	1350

11.3 Discussion

As already illustrated the scale-up spinning process for producing the yarn to be used for the fishing gears demonstrator was quite difficult and had led to a high percentage of waste of the 300 Kg of raw masterbatch produced by BIOMI.

The data obtained from the first characterization tests were discussed with CIT that was worried about the high value of elongation at break (in condition test 2 more than 155%) and the low quantity of the monofilament produced (about 50 Kg of the Condition set v2-6 starting from the initial quantity of 300 Kg).

However, also considering the constrain of the schedule of the task 3.3, it was decided to go ahead with the scale up of the demonstrator production and the spinned monofilament material was sent to CIT in order to do more preliminary characterization tests and then to produce the demonstrators.

12 Production of fishing gears

12.1 Initial characterization tests

CIT received the material from NTT divided in 2 lots, Condition (Set) VI and Condition (Set) V2-6.

CIT in its Internal Laboratory carried out the first mechanical characterizations of the spinned yarn delivered using ISO norm 2062 norm with a length sample of 250 mm and its internal testing procedures and instruments used with the normal fossil-based yarn.

The main scope was to do a comparison with the previous batches of test made with the lab scale production yarn the year before and to see if the data results were similar to what NTT found.



Figure 58 - The Dynamometer used to test the monofilament yarn

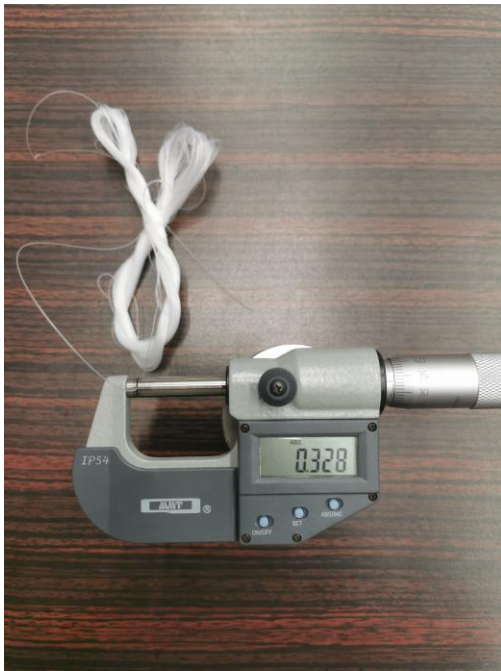


Figure 60 - Test of diameter of the monofilament

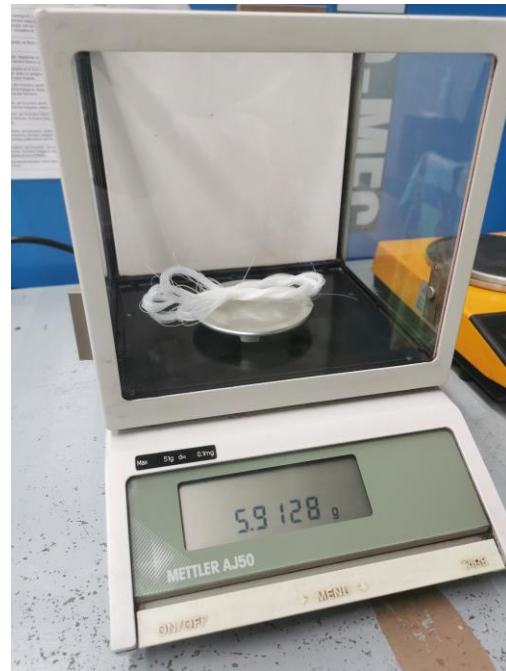


Figure 59 - Test of the linear density

Therefore, the linear density, yarn diameter, breaking load and elongation at break of different bobbins of the 2 batches of material were verified. In **Figure 61** and **Figure 62** the diagrams stress-strain of the 2 different lots are shown.

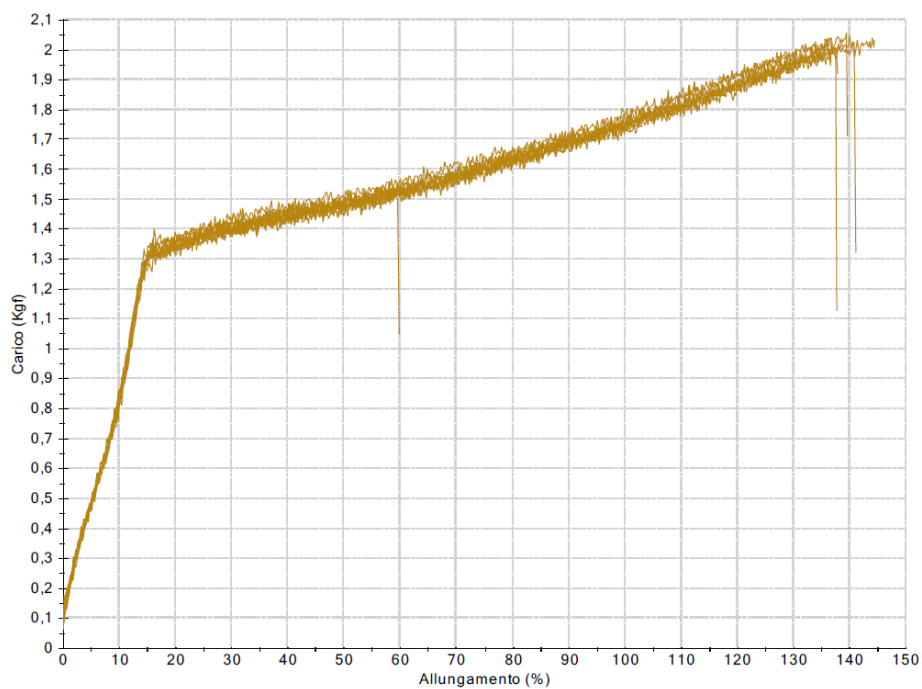


Figure 61 - Diagram Force – Elongation of sample of condition VI



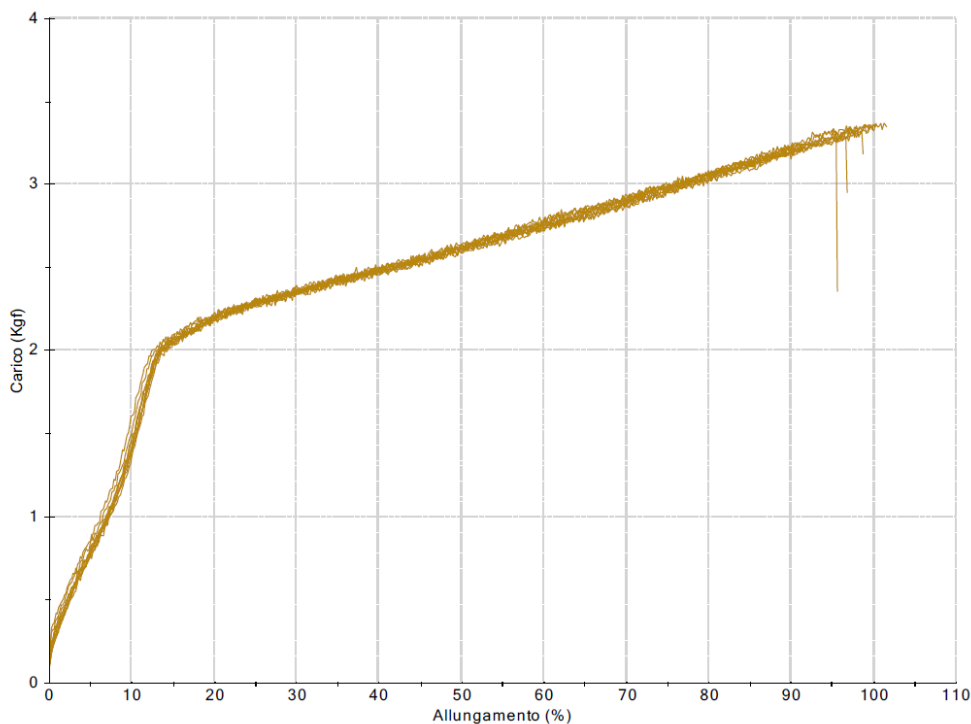


Figure 62 - Diagram Force – Elongation of sample of condition V2-6

Table 64 - Test results at CIT LAB from random spools of different sets:

SAMPLES	Linear Density (dtex)	Breaking Force (kgf)	Breaking Force N	Elongation at break (%)	TENACITY (cN/dtex)
SET 1 / SPOOL 33	1179	1,86	18,24	115,38	1,55
SET 2 / SPOOL 21	1373	3,27	32,07	95,25	2,33
SET 3 / SPOOL 49	1367	3,26	31,97	93,87	2,34
SET 4 / SPOOL 34	1320	3,18	31,19	95,77	2,37
SET 5 / SPOOL 36	1320	3,14	30,79	94,57	2,33
SET 6 / SPOOL 29	1338	3,22	31,58	94,05	2,36
MEDIA SET 2-6	1343,6	3,214	31,52	94,702	2,346

If we compare these data with the same of the standard fossil-based monofilament yarn used in the fishing gear production, usually Nylon or HDPE, we found:





Table 65 - Comparison of Remedies yarn vs Fossil based monofilament

SAMPLES	Linear Density (dtex)	Breaking Force (kgf)	Breaking Force N	Elongation at break (%)	TENACITY (cN/dtex)
CONDITION SET V1	1179	1,86	18,24	115,38	1,55
CONDITION SET V2-6	1179	1,86	18,24	115,38	1,55

NYLON MONOFILAMENT Diam. 0,35 mm	1135	5,53	54,23	38,92	4,78
Difference Set 2-6 vs Nylon	18,38%	-41,88%	-41,88%	143,32%	-50,92%
difference Set 1 - vs Nylon	3,88%	-66,37%	-66,37%	196,45%	-67,57%

Monofilament Polyethylene HDPE, 0,30 mm - color Black	682	3,36	32,95	19,5	4,83
Difference Set 2-6 vs HDPE	97,01%	-4,35%	-4,35%	385,65%	-51,43%
difference Set 1 - vs HDPE	72,87%	-44,64%	-44,64%	491,69%	-67,91%

It is clear for CIT staff that the Condition V1 spools have too low values of tenacity and breaking load to be used in industrial production and that the lot of spools of Condition V2-6 are the only ones that could be used for the scale up production of the fishing gears.

As shown in **Table 64**, the medium results of the 5 tests of samples of Condition V2 Set 2-6 showed in fact these performances:

Tenacity 2.35 cN/dtex

Elongation at break 95%

Linear density 1343 dtex

Breaking force of 3.2 kg f (= 31.52 N)

These values are comparable to the ones of the monofilament HDPE used in some nets, even if the tenacity is still half of the fossil bases ones and the elongation at break is much higher. The lower value of the tenacity, since is calculated as breaking force/linear density, is directly linked to the higher linear density of the bio-based biodegradable yarn.

The characterization tests made by CIT on the spools of raw material received have also confirmed the results of the NTT tests made during the spinning step.



In terms of tenacity the results are close to the first Lab scale monofilament trials and the differences observed in the other parameters are probably linked to the different linear density obtained in the industrial scale spinning production.

In this second series of tests, the significant difference in elongation at break observed in the CIT data compared to the NTT data was no longer present. Given that the values recorded in these tests are quite high and could pose challenges for net weaving production, CIT decided to conduct additional preliminary tests to evaluate whether this parameter could be optimized (i.e., reduced) through a heat-setting treatment.

For this reason, some spools of Condition set V2-6 were thermal treated in different ways, as described in **Table 66** below:

Table 66 - Thermal treatment tests of the Remedies monofilament Condition Set V2-6

Thermal Treatment	Linear Density (dtex)	Hot air Shrinkage (%)	Breaking load (kgf)	Elongation at Break (%)	Tenacity (cN/dtex)
Boiling in hot water for 25 seconds	1350	23	> 2,5	> 116	> 1,82
Oven at 60°C for 4 minutes	1390	18	3	112,07	2,12
Thermo-fixing with steam in vacuum autoclave at 65°C for 45 minutes	1365	//	3,32	93,21	2,38

The results of these tests indicate that the mechanical behaviour of the yarn is not much influenced by a light/medium thermal treatment and that it was not possible to increase the tenacity and lower significantly the elongation at break after the heat setting treatment of the yarn.

The remaining doubts about the workability of the yarn during the net weaving process on the fishing loom will be solved only during the actual industrial processing.

The other main concern of CIT staff was related also to the small quantity of the Condition set V2-6 yarn that was available for the industrial production (around 50 kg). This quantity is very low for a normal industrial production on a fishing net loom that usually require hundreds of Kgs to properly run. It is also worth noting that this 50 kg needs to be sufficient for the production of both demonstrators: the fishing net and the braid.

12.2 Production of monofilament fishing net

The fishing gear demonstrators to produce for the Remedies project are a net and a braided rope for a total quantity of at least 1000 m (700 m for the net and 300 m for the rope).

There are thousands of different types of nets and ropes used in the fishing sector but the final choice of the demonstrators to produce was limited by the nature of the raw material yarn available, a monofilament yarn of 0.33 mm of diameter.

Considering that main constrain and the inputs from the demo sites leaders, especially the ones from Sardinia, CIT choose to produce a monofilament knotted net with a mesh size and count that are used in Sardinia area.

In particular it was planned to produce:

Table 67 - Definition of the fishing net demonstrator

Specification of Net Panel	Mesh size Knot to Knot* - mm	Knot type	Mesh Depth	Mesh Length	stretched Mt Dept	stretched Mt Length
Bio-degradable Knotted Monofilament NET Diam. 0,33 mm 41.6 half mesh - 50 MD x 1825 ML	41.6	Double Knot	50	1825	2.08	152

* knot to knot (or half mesh) is the length of the side of the rhomb of a mesh of the net

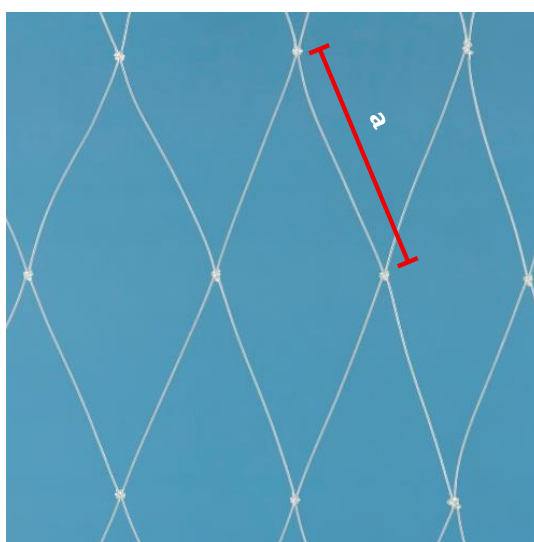


Figure 63 This is an example of 3 meshes of a double knot monofilament nylon net and marked knot to knot distance (a)

The industrial production of a monofilament fishing net is a complex process made of several steps, as shown in the **Figure 64** below:



Figure 64 - Monofilament fishing net production steps

12.2.1 Yarn preparation

The yarns are prepared for processing on the loom, often undergoing **twisting** (to increase strength) and **spool winding** (winding the yarn onto particular metallic bobbins called “shuttles” or “spools”, specific for each net loom). In this case (monofilament yarn) the twisting was not necessary but instead it was required a preliminary and not foreseen split winding of all the DIN bobbins received from NTT.

The quantity of bio-based biodegradable raw material available was in fact very low compared to the normal quantity loaded on a net loom and CIT had to carefully analyse the technical data of the net to produce in order to optimize the exact content of the raw material used by the creel and the spools of the loom.

It was necessary to calculate the exact quantity of material to be used for the fishing net and the braided rope demonstrators and divide each DIN bobbins of monofilament yarn received, rewinding them in very small package of less than 50 g each using an electronic winding machine like the one shown in the **Figure 66** but with a special single head position prepared for the DIN format parallel winding. This unforeseen step was quite time consuming because of the great number of bobbins to be prepared (400 only for the net!) in the most precise way, to avoid waste for loading on the loom of DIN bobbins or spools of uneven length.



Figure 65 - SSM Xeno Electronic Winding machine (SSM Schärer Schweizer Mettler AG – CH)



Once the 200 DIN bobbins (**Figure 66**) were ready the creel of the loom could be loaded and the yarn threaded into the net machine:



Figure 66 - The creel loaded with the 200 DIN bobbins

12.2.2 Weaving of the Net

This is the central and most important production phase, where meshes and knots are formed. Knotted nets are characterized by meshes created through the formation of knots.

CIT has a complete range of special net looms of different pitch to produce every kind of fishing net (gill net, trammel net etc.), depending on the count (the thickness) of the net to wave.

These machines, through PLC control systems, ensure the production of knotted nets with perfectly interlocked meshes.

The yarn is knotted to create the mesh structure with a simple (also called “English knot”) or double knot structure, depending on the type and the thickness of the net to produce:

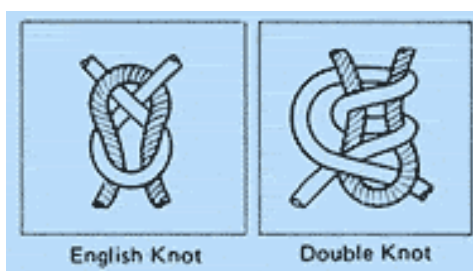


Figure 67 - Type of knot

For this specific monofilament net, CIT used a loom equipped with ceramic eyelets and a pitch suitable for weaving monofilament nets with a 0.33 mm diameter and a double knot structure.

This loom has a capacity of 200 meshes in depth, meaning it can weave nets with a maximum depth of 200 meshes. To optimize loom usage, production is organized in sets of four nets simultaneously (50 meshes × 4 = 200 meshes total).

This type of loom operates similarly to a traditional warp and weft loom: it uses one yarn from the creel (warp) and another from the shuttles (weft), located at the front of the loom.

In the **Figure 68** are shown the various components of a knotted fishing nets machine and the path of the yarn coming from the creel (green line) and from the shuttle (red line); in brown color it is possible to see the path of the weaved net that is wound on the net take-up roll.

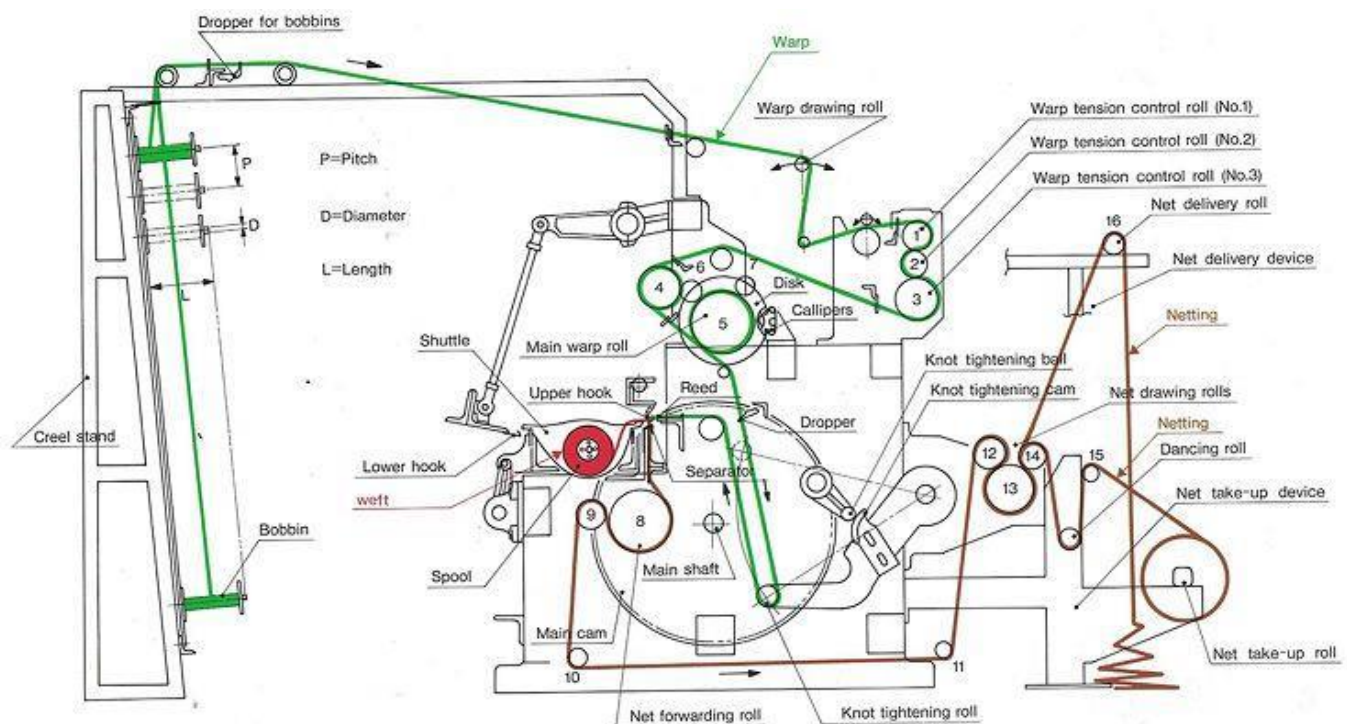


Figure 68 - General scheme of a knotted fishing net machine (Yangzhou Haili Precision Machinery Manufacturing Co., Ltd., 2025¹)

To properly load the loom, 200 special metallic shuttles are required for the weft, along with 200 bobbins for the warp, supplied from the creel.

¹ Yangzhou Haili Precision Machinery Manufacturing Co., Ltd. Netting machine construction diagram [internet]. [cited 2025 Aug 1]. Available from: <https://www.chinanetmachine.com/Content/upload/2019517680/201908051419333657729.jpg>)

The length of the net panel is generally determined by the amount of yarn available on the shuttle or spool, which typically holds less yarn than the creel bobbins.

In **Figure 69** is a picture of the loom used by CIT to produce the fishing net demonstrator:



Figure 69 - CIT Fishing Net Loom

Since the loom shuttles are typically fully loaded with the spools with the yarn to produce this specific type of net, the limited availability of the bio-based biodegradable monofilament required a manual workaround: the spools were first partially filled—up to two-thirds—with an alternative raw material, and then the monofilament yarn was wound around the outer part to complete the spool.

For this reason, it was not possible to use an automatic spool winder but instead CIT had to prepare 200 m bobbins of nylon twisted yarn used as “filler” and then add the 50 g of bio-degradable monofilament yarn to fill the metallic spool completely with a manual spool winder like the one below (**Figure 70**):



Figure 70 - The manual spool winder used to fill the spools

Once all the spools were prepared, the loom was fully loaded and threaded. The technician then configured the working parameters in the loom's PLC to weave the knotted net with the desired mesh size, taking into account the adjustments required for the subsequent heat-setting and stretching treatments.



Figure 71 - Particular of the loom's carrier where are loaded the spools



Since this Bio-based biodegradable material had never been processed by the company before, it was necessary to produce some meters of net to undergo heat-setting. This allowed the CIT's team to fine-tune the shrinkage and stretching parameters specific to the new bio-based material and the mesh size of the net to produce.

During this initial sample production, it also became clear that the mechanical cams of the loom needed some adjustment to ensure proper knot closure. This manual mechanical tuning of the cam profiles is sometimes required when changing the type of raw material—especially when its elasticity differs significantly from standard values.

This adjustment process remains somewhat artisanal and time-consuming, as it involves partially dismantling and reassembling parts of the loom each time a cam profile is modified. The loom must then be run with the yarn to verify whether the adjustment is correct or if further fine-tuning is needed.

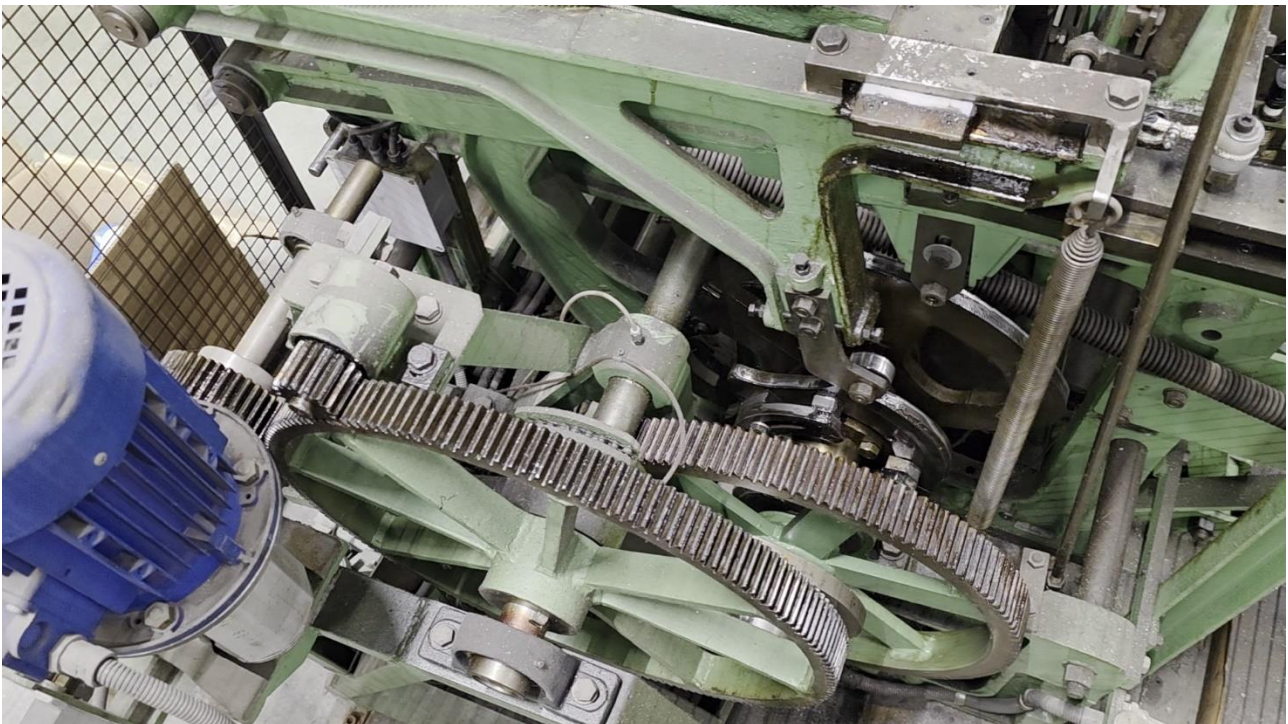


Figure 72 - Some of the mechanical cams responsible for all the synchronized movements of the loom

Thanks to all these tests and fine-tuning of the setup of the fishing net loom the production of the new bio-based biodegradable net started and was completed successfully with almost no waste of raw material. However, it was observed that the biodegradable yarn tended to "dust" or leave micro residues during processing on the loom, probably due to the mechanical stress of the weaving because of the friction that is created between the needles and hooks of the loom.

As you can see in the **Figure 73**, the needlebed of the loom is "dirty" by the residues of the yarn. A possible cause is also the total absence of lubricants and spinning oils that are normally added during the spinning of fossil-based synthetic yarn and that were not added in this case.



Figure 73 - Needlebed with the “dust” on the knitting elements

Figure 74 below shows the weaved net collected on a roll

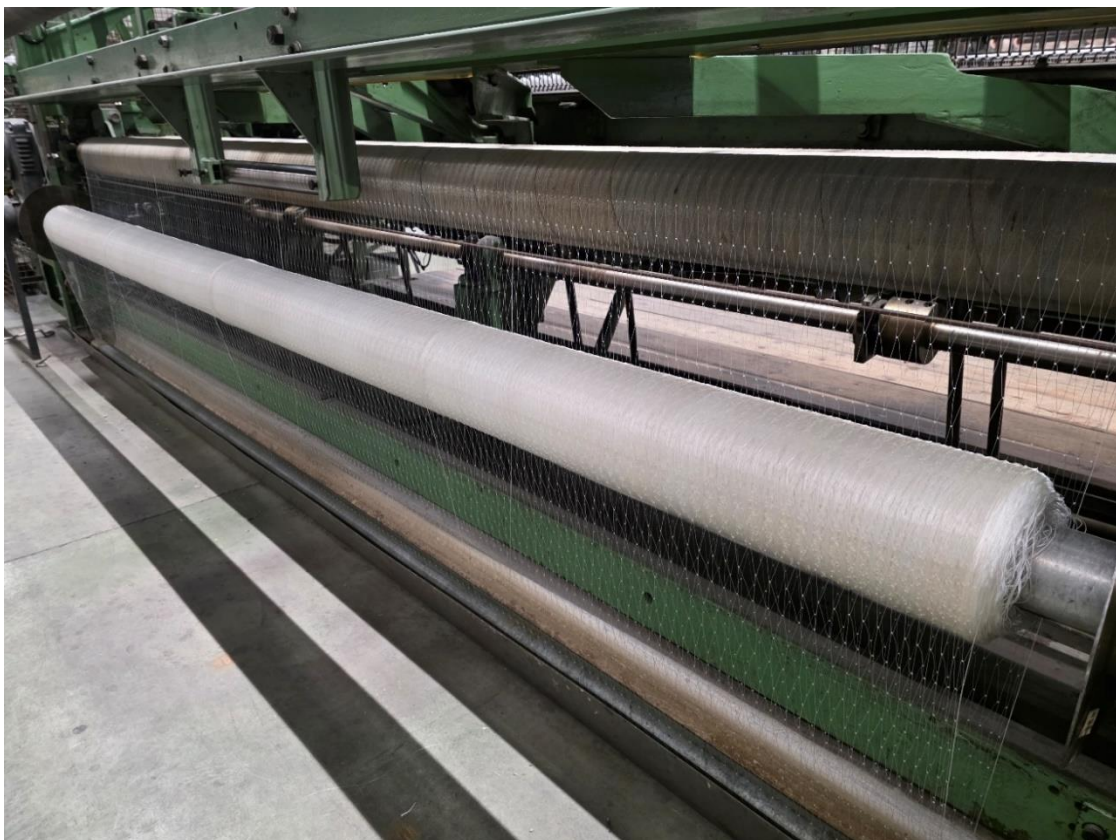


Figure 74 - The net produced by the loom is collected on a roll





12.2.3 Quality Control & Mending

Throughout and following the weaving process, rigorous quality checks are performed to ensure the net meets the required standards and is free from defects such as holes. Expert operators carefully inspect every section of the net by manually hanging and fully deploying it along its depth. If a hole is detected, it is repaired manually using the same yarn as the original net.

Net repair is a traditional craft that involves the use of specialized needles and knotting techniques—such as the sheet bend or square knot—to restore the net’s integrity. This skill has deep roots in the textile heritage of the women from Montisola, on Lake Iseo, who have long been known for their expertise in this unique application.

Despite the advanced technology of modern looms and the automation of many steps in fishing net production, this part of the process remains entirely manual. It requires exceptional handcrafting skills, typically mastered by highly trained female operators.



Figure 75 - Two operators inspect each part of the opened net



12.2.4 Stretching and Heat Setting

Once woven, the net undergoes a **stretching and heat-setting** process. This phase is crucial for the stability of the knot and the mesh. To realize this step is used a special machine with a “carrier” 25 m long where the net is threaded in special iron combs, stretched to the desired mesh size and then in loaded in a vacuum autoclave where enter the saturated steam that heat-treat the net. This process stabilizes the knots, preventing them from unraveling and making the net more resistant to wear and deformation.

In the following pictures **Figure 76, Figure 77, Figure 78, Figure 79, Figure 80** are show the net worked on this particular machine.



Figure 76 - One of the special ends where the iron combs are fixed

To avoid problems the heat setting process was made at 80 °C temperature do 20 minutes.



Figure 77 - The net loaded on the 25mt carrier of the heat setting machine





Figure 78 - A view of the 2 nets stretched on the carrier



Figure 79 - The net stretched is measured to reach the correct mesh size





Figure 80 - The opening of the vacuum autoclave after steam heat setting treatment

12.2.5 Packaging

After the heat setting the net is finally cut, often using specific machinery or simply with scissors, and packaged according to the dimensions and customer needs (e.g., in rolls or bales with a strapping machine or just some braid). Nets can be pressed to reduce volume and facilitate transport.

In this case the nets produced are packaged in 2 small bales each one containing 4 net panel of 50 MD x 1825 ML linked together in the depth direction.





Figure 81 - The operators are packing the 4 nets in one small bale





Figure 82 - The final appearance of a bale of knotted bio-degradable monofilament net



Figure 83 - Front view of the bale of net



The final net produced have been also characterized by the internal Laboratory of CIT using the standard norm ISO 1806 to control the mesh breaking load (**Figure 84**):

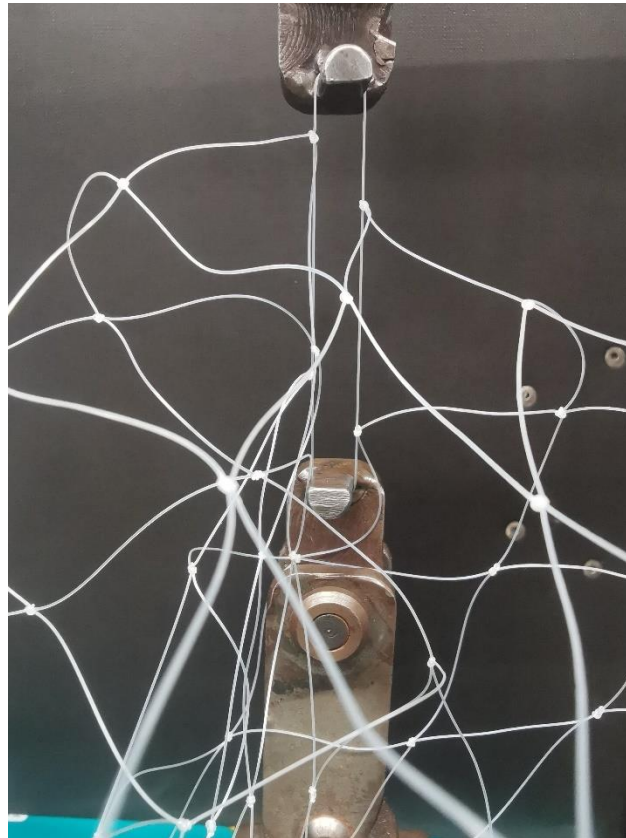


Figure 84 - Particular view of the test for determining the mesh breaking load

The result of the tests is described in the **Table 68**:

Table 68 - Results of the mechanical tests on the Bio-degradable net

Condition of trial	Breaking load (kgf)	Coeff. Of Variation	Elongation at Break (%)	Coeff. Of Variation
Speed of dynamometer: 150 mm/min Pre-tension of 200 cN Length of the sample: 79 mm	4.73	6.25%	36.88	22.07%

Some samples of the net and yarn will also be tested for aging by NTT laboratory in the next weeks and after the trial in the real-life condition of the sea of the 2 demo sites that are planned for the next months.

12.3 Production of monofilament braided rope

The remaining raw material, after the nets production, were used to produce a monofilament braid to be used with the nets, according to task 3.3. description. Considering the small quantity left and the technical characteristics of the yarn CIT decided to produce a braid of 7 mm of diameter, without core, using a braiding machine with 12 carriers.

To produce the braid, it is necessary to make several steps:



Figure 85 - Braid production steps

12.3.1 Twisting

In order to create a braid of 7 mm using 12 carriers braiding machine it is necessary to assemble and twist together several ply of monofilament yarn; in particular for each spool 15 plies of yarn were twisted together with a special one head twisting machine that assemble the 15 plies from a creel into a metered bobbin of twisted yarn for filling each spool.



Figure 86 -Take-up of the one head twisting machine

12.3.2 Spool Winding

The 12 bobbins are used to fill the 12 spools that are loaded into the carrier of the braiding machine. To realize this process is used a special parallel winder that fill up each metallic flanged spool with the twisted monofilament yarn, as illustrated in Figure 84 below:



Figure 87 - Spool winder

12.3.3 Braiding

The braiding machine is a special mechanical device used to interlace three or more strands of yarn, wire, or other flexible materials to form a braided structure. The carriers move in a specific pattern around a central axis on a braiding machine. The intertwining of threads forms the braid structure. Patterns can vary (e.g., diamond, flat, round) depending on machine settings and carrier movement

Below in **Figure 87** the technical diagram of the function of a braiding machine:

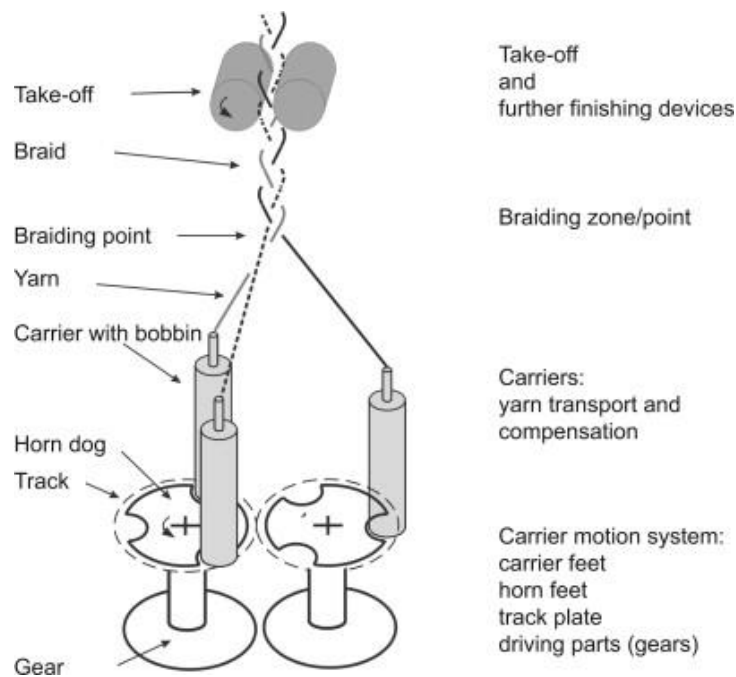


Figure 88 - Operating diagram of a braiding machine (Kyoshev, 2015²)

Each carrier is composed by the following parts (**Figure 89**):

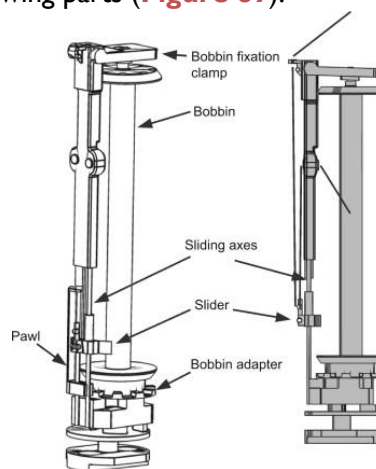


Figure 89 - Carrier components (Kyoshev, 2015²)

² Kyosev Y. Braiding technology for textiles. Cambridge: Elsevier/Woodhead Publishing; 2015



In our case it was used 12 carriers braiding machine that is normally used when you want to produce a tubular braid. The machine is closed for safety reason but from the windows is possible to see the carriers' movements:



Figure 90 - Braiding machine with a detail view of the 12 rotating carriers

The braiding machine has to be properly set-up in order to get certain condition of flexibility and strenght of the braid rope demonstrator to produce. The main parameter to be adjusted is the “pick count”: the number of braid crossings (or interlacings) per unit length of the braided product. It is a key parameter that affects the density, flexibility, strength, and appearance of the braid. The more high is the pick count per meter of the braid the more rigid, strong and heavy will be the braid.

CIT has optimized this valued in order to obtain a quite flexible braid, with nice appereance and good workability. The result is a braid “without core” with a weight of around 29 g/m.





12.3.4 Quality Control

After the production of the braid there is a step where the braid dimensions, strength, and appearance is controlled and where it is usually tested the tensile strength (breaking load) with a dynamometer.

The internal lab of CIT tested the braid produced with a big dynamometer :

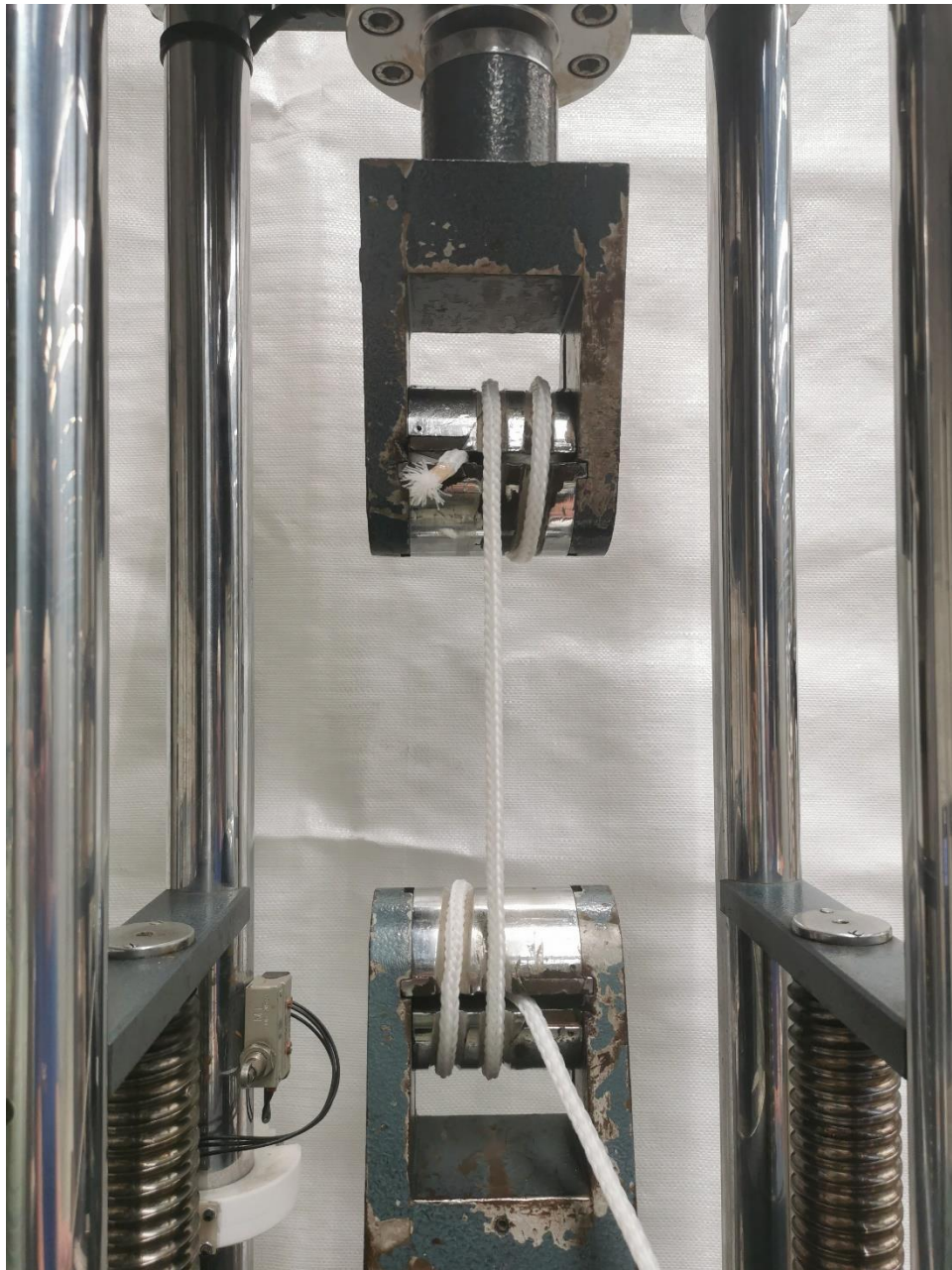


Figure 91 - Testing of the breaking load of the braid

The test report using EN ISO 2062 with a sample of braid of 250 mm is the following:





Table 69 - Mechanical characterization of the braid

Condition of trial	Breaking load (kgf)	Breaking load (N)	Elongation at Break (%)	Time of test
Test 1 Speed of dynamometer: 250 mm/min Pre-tension of 16.651 cN Length of the sample: 250 mm	329.72	3243.45	123.83	161 s
Test 2 Speed of dynamometer: 250 mm/min Pre-tension of 16.651 cN Length of the sample: 250 mm	325.20	3189.12	111.22	143 s
Average values	327.46	3211.28	117.525	

The graphics of the test is shown in **Figure 92**:

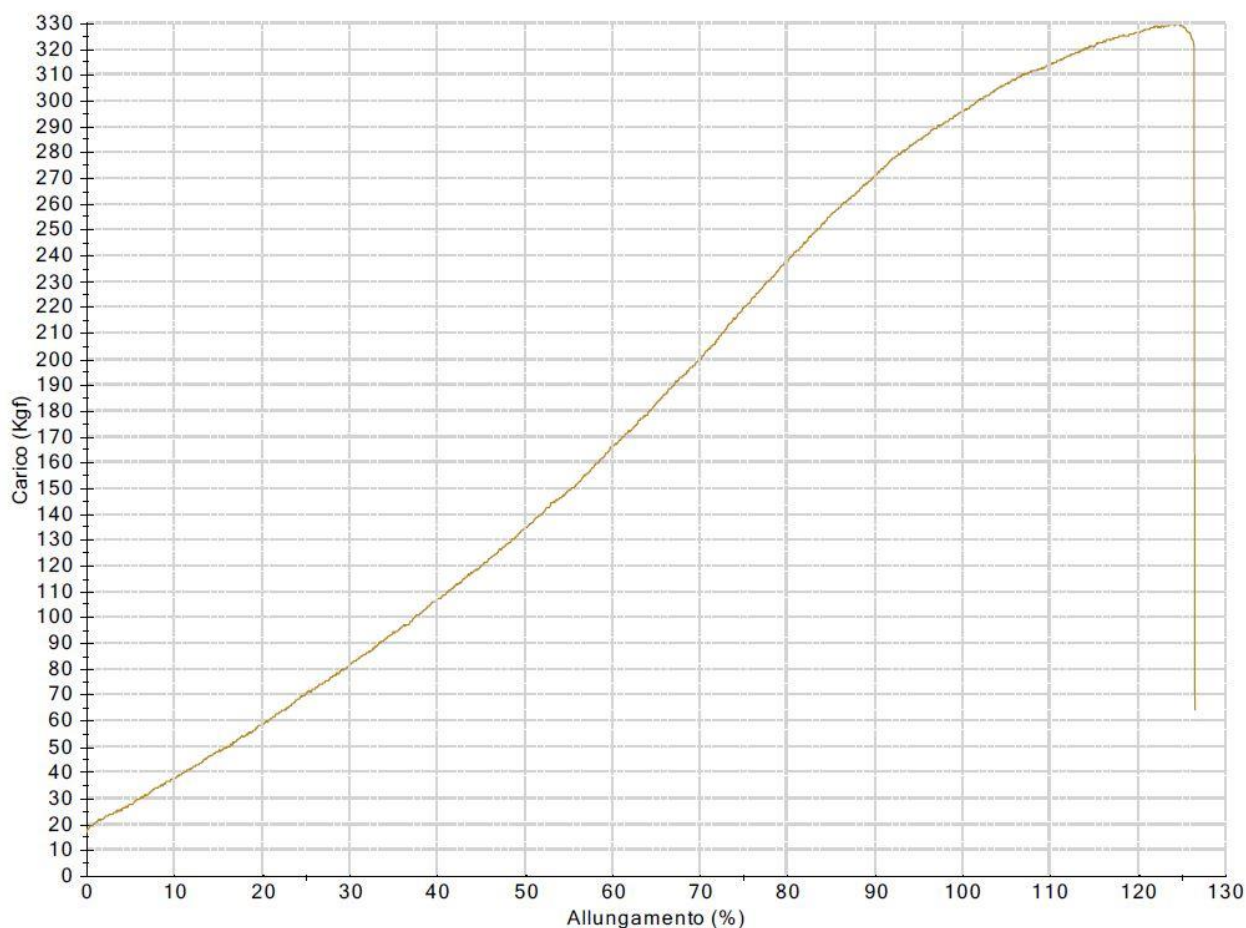


Figure 92 - Stress - Strain diagram of the braid tested

Please note that, in order to preserve as much of the produced braid as possible, extensive testing was avoided. Only two tests were conducted, as the values appeared to be quite stable thereafter.



In **Figure 93** is possible to see the aspect of the monofilament braided rope produced.



Figure 93 - The aspect of the braided rope made of bio-degradable monofilament

12.3.5 Final Winding

After the quality check, the braided rope is parallel winded on a bobbin, usually with carton flange for this type of article (see **Figure 94**).

Thanks to all the preliminary studies and the attention during various production steps the waste was minimal and the final quantity of the rope demonstrator produced was 510 m, exceeding the minimum KPI for this type of deliverable (quantity of rope > 300 m).



Figure 94 - The final aspect of the bobbin of braided rope for Remedies project

13 Demo sites

The fishing net and the braided rope demonstrators produced by CIT will be tested in ongoing duration of the task 3.3 of Remedies project by professional fishermen in 2 different demo sites in Sardinia and Cyclades areas to see how they behave in real life condition and to receive feedback about handling and applicability and how they compare to the standard fossil-based fishing gears.

One of the areas involved in the future tests has been already identified: it is located in Sardinia, in the Sinis Peninsula. The details of the Cyclades demo site and the demonstration activities of the biodegradable fishing gear at the demo, as well as any other replication site during the REMEDIES project, will be followed and reported in the next periodic reports, dissemination and exploitation activities reports, to capture the impact of the demonstrated fishing gear.

13.1 Sinis Peninsula - Sardinia

Sardinia, with its strategic position in the heart of the western Mediterranean, is a region of extraordinary natural, cultural, and environmental value. The island is known for the beauty of its coastline, the richness of its marine and terrestrial biodiversity, and the presence of delicate and precious ecosystems. However, despite its high environmental and landscape value, the sea surrounding Sardinia is also affected by pollution, particularly plastic. Its central location in the Mediterranean and the action of marine currents cause microplastics and floating debris to accumulate along its coasts, posing a concrete threat to the marine ecosystem and traditional local activities, such as fishing.

In this context, the Sinis Peninsula located on the western coast of the island, within the "Penisola del Sinis - Isola di Mal di Ventre" Marine Protected Area was selected as a demo site as part of Remedies project aimed at testing new technological instruments and biocompatible equipment for monitoring and preventing marine pollution. The Sinis is a region that combines environmental value and cultural significance: it is home to important internationally protected wetlands, such as the Cabras Pond, ancient archaeological sites such as the ancient Phoenician-Punic city of Tharros, and a local community deeply rooted in both sea and land activities.

Precisely because of these characteristics, the Sinis is ideally suited to testing innovative technologies for marine protection, such as sensors for detecting microplastics, sustainable collection systems, and tools for environmental mapping and monitoring. The project has a twofold objective: first, to evaluate the effectiveness of low-impact technological solutions in a real-world context; second, to promote a replicable intervention model based on collaboration between scientific institutions, local authorities, and local communities.

At a time when marine protection is a shared priority at the European and global levels, initiatives like this represent a concrete step toward building a more sustainable future, where innovation and respect for the environment go hand in hand.





Figure 95 - Sardinia demo site - Sinis Peninsula



Figure 96 - Image of the coast of Sinis Peninsula





Figure 97 - Image of a shore in Sardinia demo site

13.1.2 Testing of biocompatible fishing nets in the Sinis Marine Protected Area

As part of the European project dedicated to testing innovative solutions for marine environmental protection, one of the key actions planned for the Sinis Peninsula demonstration site involves testing fishing nets made from biocompatible materials. The initiative will take place within the "Sinis Peninsula – Mal di Ventre Island" Marine Protected Area, an area of high natural value that, thanks to its biodiversity and the presence of traditional fishing activities, represents an ideal context for this type of experiment.

The test will be conducted in collaboration with a professional fisherman (see **Figure 98**) operating in the area, with the aim of integrating technological innovation into sustainable fishing practices that are compatible with the marine environment. The experimental nets will be used in real fishing conditions between August and November to evaluate their performance in different seasonal and operational contexts.

During the testing phase, data will be collected on the durability of the materials, the behaviour of the nets at sea, the degree of degradation over time, and the catch efficiency compared to conventional nets. All tests will be documented through photos and videos, both onboard and underwater, to visually monitor the gear's performance and produce useful materials for the project's scientific and educational dissemination.

This activity represents a concrete step toward reducing the impact of fishing gear on the marine environment. Conventional nets, once lost or discarded, contribute significantly to ghost fishing and plastic pollution. The adoption of alternative materials, more easily biodegradable or recyclable, could help prevent these impacts, provided their functionality and safety for those who use them are guaranteed.





The direct involvement of local fishermen, combined with a scientific approach to monitoring and evaluation, is essential to promoting a concrete and shared shift toward more sustainable and responsible fishing, capable of combining innovation, biodiversity protection, and the valorisation of traditional coastal economies.



Figure 98 - Images of a fisherman and its fishing net





Figure 99 - A typical knotted fishing net with its braided rope



14 Conclusion and next steps

The Task 3.3 of Work Package 3 “Circular solutions for preventing plastic waste” of the REMEDIES project has successfully tackled the challenge of developing biodegradable fishing gear, aimed at reducing marine pollution caused by conventional plastic materials.

Through a comprehensive experimental pathway, the task 3.3 identified, tested, and optimized bio-based polymer blends suitable for producing monofilament and multifilament yarns for fishing nets and ropes.

After extensive laboratory trials and mechanical testing, the PBS/PBAT 85:15 (C2.2) compound emerged as the most promising candidate for industrial-scale monofilament production. This material demonstrated good processability and acceptable mechanical properties. While these values are lower than those of fossil-based materials like nylon and HDPE, they are sufficient for fishing gear demonstrator production.

The industrial scale-up phase revealed several challenges, particularly during the yarn stretching process, which required multiple optimizations. Despite these difficulties, approximately 50 kg of usable yarn was produced from 300 kg of compound, enabling the creation of demonstrators.

Although the fishing gear production phase presented some challenges, CIT successfully completed the two demonstrators planned for Deliverable D3.2, meeting the June 2025 deadline: a knotted monofilament fishing net with 0.33 mm diameter and 41.6 mm mesh size, and a 7 mm braided rope produced using a 12-carriers braiding machine.

Mechanical testing confirmed the performance of the materials, with the net achieving a breaking load of 4.73 kgf and elongation of 36.88%, and the rope reaching a breaking load of over 327 kgf. These results validate the technical feasibility at TRL7 of the developed monofilament biobased biodegradable material.

The demonstrators will be sent to pilot demo sites, particularly in the Sinis Peninsula (Sardinia) and in Cyclades area, for real-world testing by professional fishermen. These tests will start from August 2025 until the end of the task in M42 and will assess the handling, durability, environmental degradation, and catch efficiency of the biodegradable fishing nets and ropes.

NTT will also do UV tests on the demonstrators produced to verify the aging of the material exposed to UV.

In summary, the REMEDIES project demonstrated the industrial feasibility of producing biodegradable fishing gear. While further improvements are needed to match the performance of fossil-based materials, the project marks a significant step toward a more sustainable future and contributes meaningfully to the fight against marine plastic pollution.





Annex I - Parameters related to the extrusion process

Laboratory scale multifilament production: first phase

Material	Fibre reference	Pump speed (rpm)	Volumetric output (cm ³ /min)	Throughput (g/min)	Wall shear rate (s ⁻¹)	Extruder Speed (rpm)	Extruder Torque (N•m)	Spinneret pressure (bar)
2. PBS/PBAT	“2” Fibre 1	29.56	17.74	21.28	387.21	9.43	0.93	47
	“2” Fibre 2*	29.56	17.74	21.28	387.21	9.3	0.85	49
	“2” Fibre 3	29.56	17.74	21.28	387.21	9.79	0.80	51
6. PBS/PBAT	“6” Fibre1	29.56	17.74	23.06	387.21	8.89	0.85	43
	“6” Fibre2	29.56	17.74	23.06	387.21	8.89	0.85	43
9. PLA/PCL	“9” Fibre 1*	29.56	17.74	21.28	387.21	10.96	0.73	36
	“9” Fibre 2	29.56	17.74	21.28	387.21	11.6	0.80	32
	“9” Fibre 3*	29.56	17.74	21.28	387.21	11.25	0.72	25
	“9” Fibre 4	29.56	17.74	21.28	387.21	10.82	0.70	24
	“9” Fibre 5	29.56	17.74	21.28	387.21	15.61	0.86	21
11. PBS/PHA	“11” Fibre 1*	7.6	4.56	5.47	99.55	3.19	0.67	-3
	“11” Fibre 2*	7.6	4.56	5.47	99.55	4.59	0.44	-2
	“11” Fibre 3*	29.56	17.74	21.28	387.21	9.22	0.90	14
	“11” Fibre 4*	29.56	17.74	21.28	387.21	9.92	0.78	19
	“11” Fibre 5	29.56	17.74	21.28	387.21	7.78	0.86	23
	“11” Fibre 6	29.56	17.74	21.28	387.21	8.73	1.03	28
12. Starch/PBAT:PHA	“12” Fibre1	29.56	17.74	21.28	387.21	8.17	0.98	30
	“12” Fibre2	29.56	17.74	21.28	387.21	9.68	0.75	34
	“12” Fibre3	29.56	17.74	21.28	387.21	8.4	0.83	35
	“12” Fibre4	29.56	17.74	21.28	387.21	8.92	1.03	38
13. Starch/PBAT	“13” Fibre1	29.56	17.74	23.06	387.21	9.74	1.22	96
	“13” Fibre2	29.6	17.76	23.09	387.21	9.90	1.10	99
	“13” Fibre3	29.56	17.74	23.06	387.21	9.92	1.27	96
	“13” Fibre4	29.56	17.74	23.06	387.21	7.80	1.10	98

* Fibres obtained under an unstable spinning process that may lack filaments and possess other defects.





Laboratory scale multifilament production: second phase

Material	Filament reference	Pump speed (rpm)	Volumetric output (cm ³ /min)	Throughput (g/min)	Wall shear rate (s ⁻¹)	Extruder Speed (rpm)	Extruder Torque (N•m)	Spinneret pressure (bar)
Material A	A_Filament 1*	36	22	25.92	472	11	1.28	109
	A_Filament 2	12	7	8.64	157	4	0.94	50
	A_Filament 3*	36	22	25.92	472	10	1.01	128
	A_Filament 4	36	22	25.92	472	11	1.10	93
	A_Filament 5*	36	22	25.92	472	12	1.09	85
	A_Filament 6*	36	22	25.92	472	12	1.03	86
	A_Filament 7*	36	22	25.92	472	11	1.09	102
	A_Filament 8	36	22	25.92	472	11	1.08	114
	A_Filament 9	48	29	34.56	629	15	1.47	137
	A_Filament 10	36	22	25.92	472	15	1.47	115
Material B	B_Filament 1	12	7	8.64	157	4	0.75	66

* Filaments obtained under an unstable spinning process that may lack filaments and possess other defects.

Laboratory scale multifilament production: third phase

Material	Filament reference	Pump speed (rpm)	Throughput (g/min)	Spinning Speed (m/min)	Pressure (bar)	Melt pump (°C)	Melt temperature (°C)	Transfer line (°C)
Material C	C_Filament 1*	44	35.24	470	47	180	180	163
	C_Filament 2*	44	35.24	150	51	180	179	163
	C_Filament 3*	20	16.02	155	36	17	165	153
	C_Filament 4	20	16.02	255	26	170	164	153
	C_Filament 5	44	35.24	430	66	170	172	153
	C_Filament 6	44	35.24	130	67	170	174	153

* Filaments obtained under an unstable spinning process that may lack filaments and possess other defects.

