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Environmental Impact Assessment of Thermoplastic Pultrusion of GF-PP Pre-Consolidated Tapes

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Abstract. This work focuses on the pultrusion of pre-consolidated tapes made of virgin polypropylene reinforced with glass fiber. A specially designed laboratory-scale pultrusion line was used, consisting of a heating/forming mold, a cooling mold, and the pulling system. A life cycle assessment was conducted to evaluate the environmental impact of producing a pultruded composite material with a constant cross-section of 100 mm² and a length of one meter. The cradle-to-gate approach was chosen to model the pultrusion process, which involves the three stages mentioned above. The analysis was performed using the CML 2016 method in the LCA for Experts (Sphera) software. The data used in this work to model the cradle-to-gate scenario are mainly derived from experimental measurements taken during the pultrusion process using sensors and from the literature. The specific Energy Consumption (SEC) was calculated for both operational conditions (1.41 MJ/m at v120 to 0.905 MJ/m at v180). Despite the defects found, the samples taken from the pultruded profile showed significant interlaminar shear strength (120 mm/min of 83.7 ± 9.6 MPa compared to 63.5 ± 17.3 MPa at 180 mm/min).

Introduction

Thermoplastic matrix composites offer many significant advantages, both mechanically and physically, compared to the more common fiber-reinforced thermoset composites [1], [2]. For this reason, in recent years they have attracted the interest of industrial sectors requiring high-performance materials, such as the nautical, aerospace, and automotive sectors. Another attractive feature is their ability to be post-formed and welded. However, their high viscosity during processing has prevented their widespread use as a composite matrix. This characteristic makes impregnation with the reinforcement difficult, increasing the risk of defects and, consequently, production costs [3]. For this reason, research is increasingly pushing for solutions that utilize pre-consolidated materials, thus reducing the viscosity of thermoplastics[4], [5]. Thermoplastic pultrusion is the most advantageous composite manufacturing process for producing continuous profiles of theoretically infinite length [4], [6], [7]. A non-reactive pultrusion line for thermoplastic composites consists of pre-impregnated tapes, a guiding system, a preheating chamber, a heated forming die, a cooling die, a puller system and a cutting saw. In recent years, this process has gained popularity in various industries, including marine, automotive, aerospace and construction, due to its ability to produce lightweight, strong and recyclable components [6], [8], [9], [10]. Indeed, with the increasing demand for more sustainable manufacturing practices, thermoplastic pultrusion represents an opportunity to promote recyclability and thus reduce environmental impact compared to traditional thermoset pultrusion. However, to date, the number of studies and publications in the field of thermoset pultrusion is an order of magnitude higher than that of thermoplastics, despite the advantages offered by the latter. To evaluate the sustainability of a product or process, it is possible to resort to Life Cycle Assessment. It is a structured and internationally standardized method that allows us to quantify the potential environmental and human health impacts associated with a good or service, based on their resource consumption and emissions [11]. In this context, the primary objective of this work is to conduct a cradle-to-gate preliminary LCA analysis of the thermoplastic pultrusion of pre-consolidated GF/PP tapes using experimentally measured energy data. Furthermore, the study further investigates how varying pultrusion speed affects specific energy consumption (SEC), the associated environmental impacts in different midpoint categories, and interlaminar shear strength (ILSS) as an indicator of consolidation quality. The pultrusion speed was chosen as the primary process variable because it directly controls the residence time in the heated mold. Therefore, evaluating its effect allows for a preliminary assessment of process intensification strategies from both an environmental and mechanical perspective. This approach allows us to quantify the extent to which increasing production speed effectively reduces environmental burdens per functional unit and whether such reductions occur without compromising interlaminar performance. By integrating environmental and mechanical parameters into the same experimental framework, this study provides a first process-level quantification of the relationship between production rate, energy intensity, and interlaminar integrity in thermoplastic pultrusion.

Materials and Methods

A commercial tape produced by CompTape BV (Delft, Netherlands) is composed of a continuous filament E-glass roving (Owens Corning SE4849, tex. number 2400) and a polypropylene matrix (Moplen RP348U). The pre-consolidated tapes have a width of 6.35 mm, and a thickness of about 0.6 mm. Thirty-four tapes were used to produce a composite profile with a rectangular cross-section 25 mm wide and 4 mm thick. The number of tapes used is sufficient to oversaturate the heating die by 30%, increasing the fiber volume fraction of the pultruded product. The thermoplastic matrix must be heated above its melting temperature (Tm), consolidated, and then cooled to obtain a solid composite profile. Therefore, the laboratory-scale pultrusion line used consists of a preheating die to gradually increase the temperature, a heating/forming die where the polymer softens and melts, resulting in compaction, a cooling die responsible for solidification, and finally, the traction system.

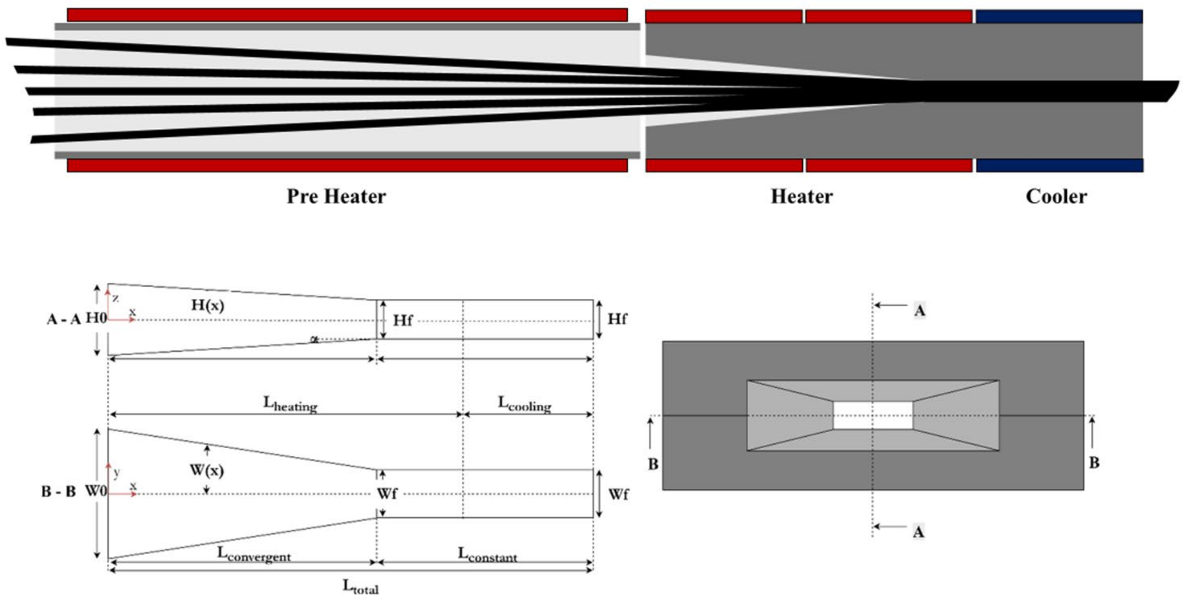

Fig. 1. Thermoplastic pultrusion dies

The heating/forming die is 180 mm long and divided into a 160 mm long converging section and a 20 mm long constant section. The cooling system is located in the next 100 mm long section of the mold. Fig. 1 shows the geometry of the mold cavities. Thermal energy is provided by three pairs of electric heating plates monitored by J-type thermocouples and regulated by PID controllers to maintain the temperature at the Tset point ± 5 °C. The cooling system consists of a water-cooling system regulated by an industrial chiller with a temperature setpoint of 13 °C. To ensure process continuity, a track conveyor at the end of the line acts as a towing system, allowing the material to move along the entire line. Table 1 shows the process parameters. DSC analysis performed on the PP made it possible to determine the temperature window and process speeds. In particular, the temperatures of the die zones were set to ensure that the melting range of the PP was completely exceeded in the hot section, ensuring adequate viscosity reduction with a consequent improvement in impregnation, while in the cooling section, controlled passage through the crystallization region was ensured in order to stabilize the microstructure before extraction. The pulling speed was the only variable modified to modulate the residence time in the die, while the other process parameters remained unchanged.

Table 1. Process parameters

		Temperature		**Velocity**
	Pre-Heater	**Heating Die**	**Set point chiller**	**[mm/min]**
1°	90°C	200°C	13°C	120
2°	90°C	200°C	13°C	180

To verify that the chosen process parameters, under steady-state conditions, allowed the temperatures at the core of the pultruded material to be reached sufficiently to allow the polymer to melt and solidify, the mobile thermocouple method was used [12].

Life Cycle Assessment. Life Cycle Assessment (LCA) is the internationally recognized method used to assess the environmental performance of a product or of a service. ISO 14040:2006 [13]. This study aims to assess the environmental impacts of a composite material made with glass fiber (GF) and polypropylene (PP) through a cradle-to-gate LCA, shown in Fig. 2.

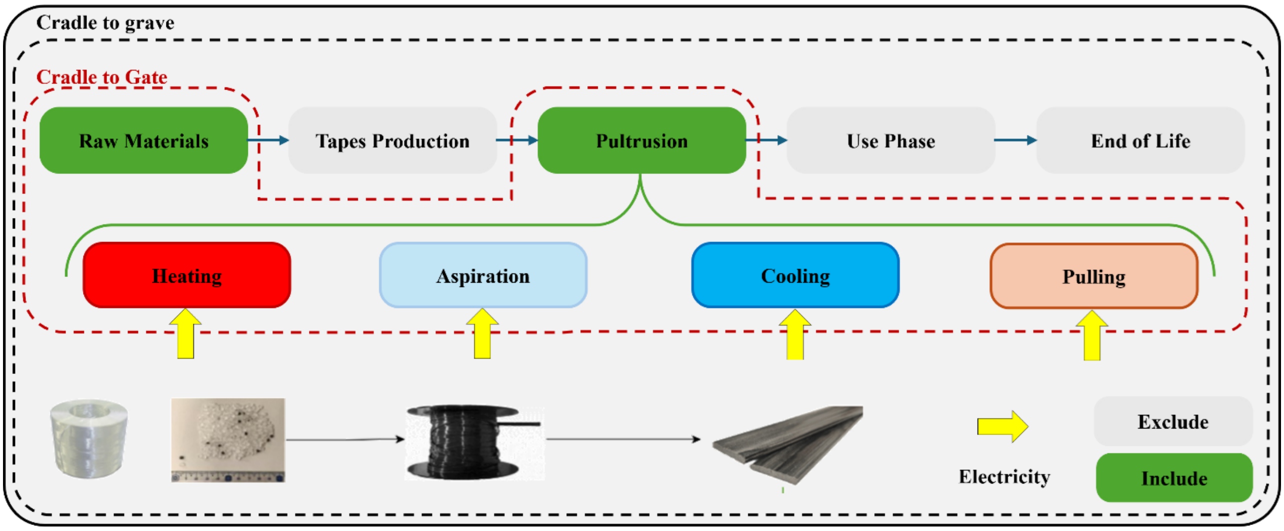

Fig. 2. System boundary

Functional unit (FU) is defined as 1 meter of pultruded glass-polypropylene composite (GF/PP) profile, having a rectangular solid cross-section of 25 × 4 mm, made under steady-state process conditions. The mass corresponding to FU is around 0.126 kg, measured experimentally. Primary data were acquired over a total length. However, the last meter made was selected for each experimental trial to avoid the transient phase. All matter and energy fluxes are normalized with respect to the functional unit. The analyses have been carried out by using LCA for Experts - Sphera (GaBi). The LCA model used is the CML 2016 impact assessment method (August 2016 version). This method uses midpoint indicators to model the effects of substances on the environment at an early stage (also known as the problem-oriented approach), which minimizes uncertainties. The environmental impact category chosen are: Global Warming Potential (GWP 100) [kg CO_2 eq], Abiotic Depletion Potential – Fossil Fuels (ADPf) [MJ], Abiotic Depletion Potential – Elements (ADPe) [kg Sb eq], Acidification Potential (AP) [kg SO_2 eq], Eutrophication Potential (EP) [kg PO_4^{3-}

eq], Ozone Depletion Potential (ODP) [kg CFC-11-eq], Photochemical Ozone Creation Potential (POCP) [kg C2H4-eq]. Thus, raw material production (fiber, PP) is included in the system boundaries, while tapes production in this first stage of analysis was omitted as it was considered negligible compared to the raw material production stage and process. The authors considered focusing on the process by neglecting all transportation, infrastructure (machinery, building), maintenance, personnel, and measuring instruments at this first stage, according to the cut-off principle.

Life cycle inventory (LCI). This section is devoted to the second phase of the LCA study, the Life Cycle Inventory (LCI), in which all input and output flows present in the system boundary are reported. Table 2 reports all elementary flows used to model the cradle-to-gate scenarios, which are mainly derived from experimental measurements made during the pultrusion process using current and voltage sensors and from the LCA modeling software database. Current and voltage sensors were used during the process to monitor the power absorbed by each element in the line and its power consumption. As shown in Fig. 3, junction boxes were used for monitoring to allow measurement of both current and voltage and a DAQ connected to a pc for real-time data acquisition. A sampling frequency of 20 kHz was chosen to perform the power analysis. For energy calculation, reference was made only to the active power required to carry out experimental tests, considering the different systems present (mono-phase and three-phase). Specific energy consumption (SEC) was adopted to evaluate the energy efficiency of the pultrusion process. It is energy consumption to make the F.U. unit by pultrusion and in our study it is expressed in Eq.1. Where E (MJ) is electrical energy consumption during the process to make the F.U.

$$\mathrm{SEC} = \frac{\mathrm{E}}{\mathrm{F.U.}} \tag{1}$$

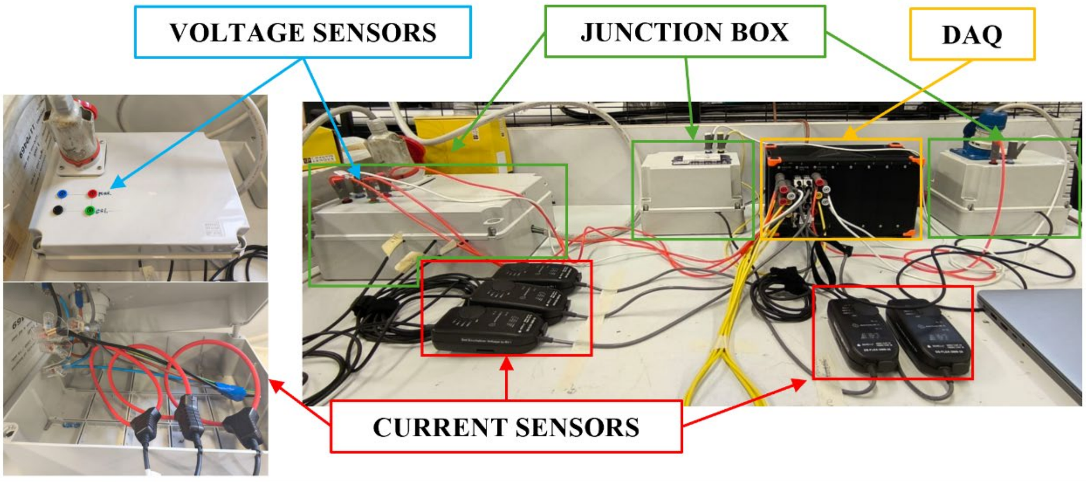

Fig. 3. Set up of electricity measurement

Table 2 reports the data used in this work to model the cradle-to-gate scenario, which are mainly derived from experimental measurements taken during the pultrusion process using current and voltage sensors and from the database of software.

Table 2. Life Cycle Inventory

Inventory	**Measure Units**			**Source**
Raw Materials				
E - Glass fibers (GF)	kg	0.082	0.082	**Gabi Database**
Polypropylene (PP)	kg	0.044	0.044	**Gabi Database**
Thermoplastic Pultrusion				
INPUT		**T200-V120**	**T200-V180**	
Tapes GF/PP	kg	0.126	0.126	**Primary Data**
Electricity	MJ			
Suction hood		0.434	0.282	**Primary Data**
Heating Die		0.603	0.361	**Primary Data**
Cooling Die		0.303	0.202	**Primary Data**
Caterpillar		0.068	0.060	**Primary Data**
Total [MJ]		1.41	0.905	
OUTPUT				
Pultruded composite	kg	0.126	0.126	

For the modeling of upstream (background) flows such as glass fibers and polypropylene, it was not possible to use primary inventories directly referring to the suppliers used in the experimental trials. Therefore, secondary datasets from the GaBi database were used, selected to maximize consistency in terms of production technology and geographic representativeness. Specifically, fiber was represented through a dataset with reference to Germany, while PP was modeled through an average EU-28 dataset. It should be emphasized that these datasets do not necessarily correspond to the exact specifications of the materials actually used and therefore introduce systematic uncertainty into the estimation of absolute impacts associated with raw materials. However, since the comparison between scenarios was set up with equal bill of materials and with differences mainly on speed as a process parameter, the use of datasets is considered appropriate for the comparative analysis, with the understanding that the sensitivity of the results to the choice of feedstock dataset is discussed in the uncertainty/limits section. As mentioned above, for the electricity consumed by the pultrusion line (foreground), the inventory was constructed from experimental current and voltage measurements, and the associated impact was calculated using an Italian electricity grid mix, consistent with the location of the production site and the specific emissions of the national electricity system.

Interlaminar shear strength test. A mechanical interlaminar shear strength test was performed on the pultruded profile in accordance with the ISO D2334. The mechanical test was performed using the Galdabini universal testing machine. At least 5 samples were tested to obtain the ILSS according to Eq. 2.

$$\mathrm{ILSS} = 0.75 * \frac{\mathrm{Pm}}{\mathrm{b} * \mathrm{h}}, \tag{2}$$

Results and Discussion

At a visual inspection, both produced profiles appeared well compacted and with constant cross section, even if the external surface presented marked irregularities, as visible in Fig. 4.
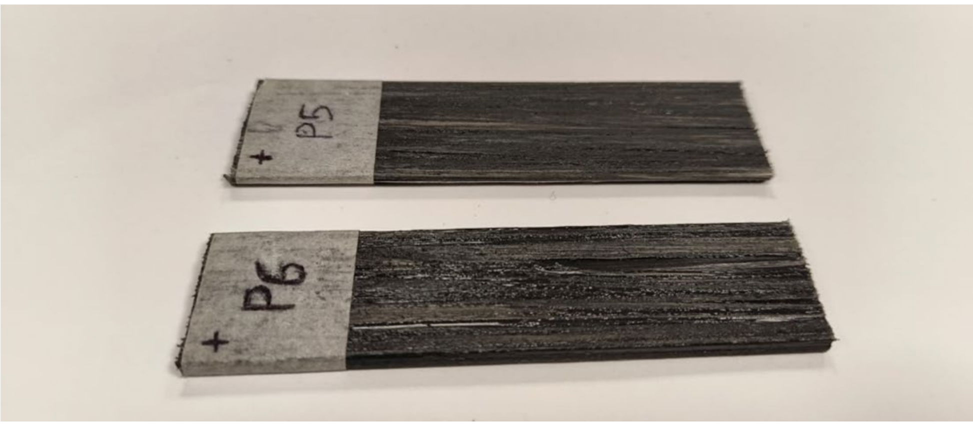
Fig. 4. Pultruded composite (P5 – T200 v120; P6 – T200 v180)

Life Cycle Impact Assessment. This section is dedicated to the third phase of the LCA study, the life cycle impact assessment (LCIA), in which the life cycle inventory information on elementary flows is translated into the chosen environmental impact categories. The analysis is performed by using the CML 2016 method in the LCA for Experts (Sphera) software.

Table 3. Life Cycle Impact Assessment

Impact	**T200-v120**	**T200-v180**
Photochemical Ozone Creation Potential (POCP) [kg C2H4-eq]	9.62	9.08
Global Warming Potential (GWP 100) [kg CO_2 eq]	0.37	0.33
Eutrophication Potential (EP) [kg PO_4^{3-} eq]	10.2	9.19
Acidification Potential (AP) [kg SO_2 eq]	1.33	1.25
Abiotic Depletion Potential – Elements (ADPe) [kg Sb eq]	7.52	7.51
Abiotic Depletion Potential – Fossil Fuels (ADPf) [MJ]	6.95	6.37
Ozone Depletion Potential (ODP) [kg CFC-11-eq]	5.28	4.17

As can be seen from the results shown in aggregate in Table 3 for all impact categories analyzed, the scenario processed at the highest pull speed (v 180 mm/min) has lower total impacts, with the only marginal exception of ADPe, which remains essentially unchanged as it is dominated by upstream material contributions rather than process-related energy consumption. Overall, the results clearly indicate that increasing the pull rate leads to a systematic improvement in environmental performance per functional unit. The observed reductions in environmental impacts are mainly due to the decrease in specific energy consumption per meter of pultruded profile. The total energy requirement (SEC) decreases from 1.41 MJ/m at v120 to 0.905 MJ/m at v180, representing a reduction of approximately 35.8 percent. All energy subsystems benefit from increased traction speed. Heating energy decreases from 0.603 to 0.361 MJ/m (-40.1%), intake from 0.434 to 0.282 MJ/m (-35.0%), cooling from 0.303 to 0.202 MJ/m (-33.3%), and traction from 0.068 to 0.060 MJ/m (-11.8%). Despite the reduction in absolute values, the relative distribution among subsystems remains approximately constant, with heating accounting for about 40-43% of total energy demand, extraction 31-32%, cooling 21-22%, and traction 5-7%. From a process perspective, this behavior reflects the partial amortization of quasi-stationary thermal and auxiliary loads at a higher production rate, resulting in reduced energy intensity per unit length. To perform a comprehensive analysis, the authors reported the impacts in disaggregated form in Figures 5 - 11 to evaluate hotspots by impact category.

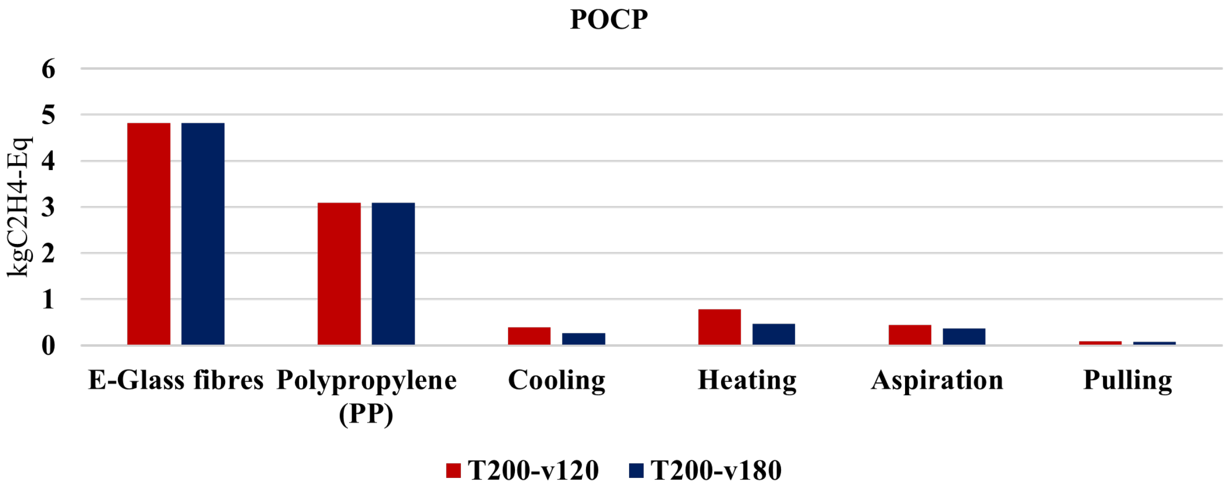

Fig.5. Non-aggregate impacts of POCP

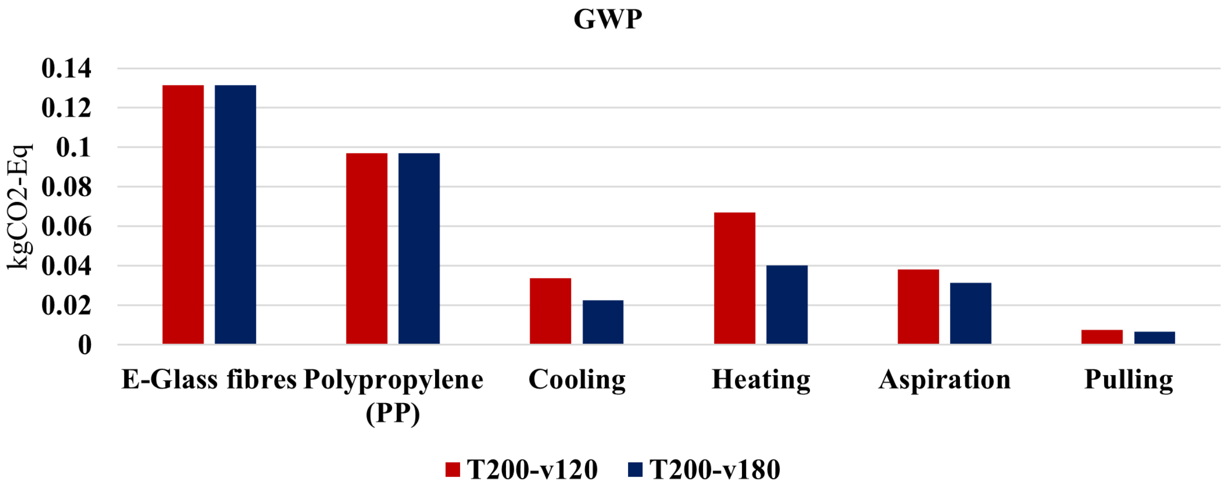

Fig. 6. Non-aggregate impacts of GWP

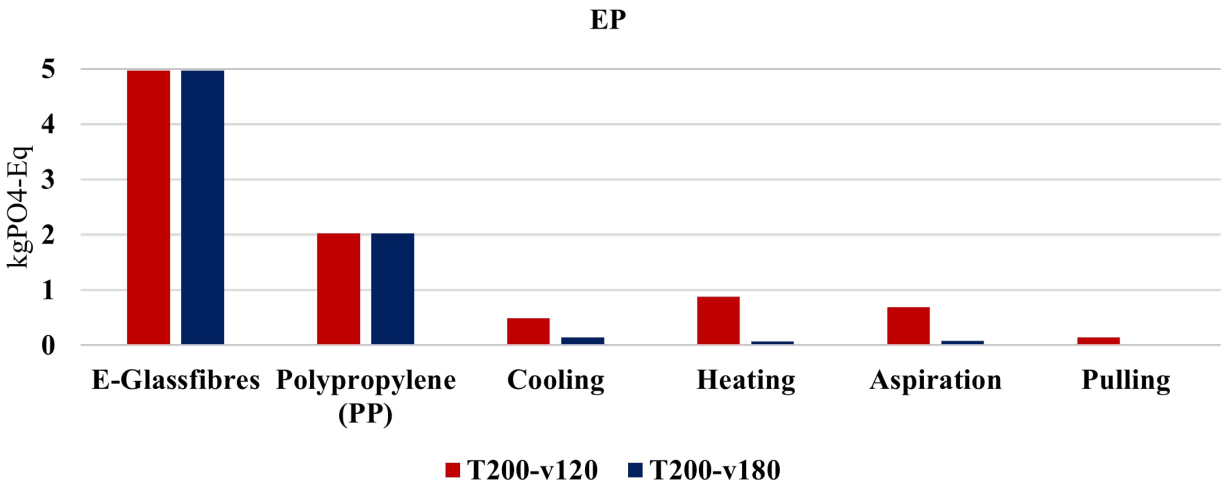

Fig.7. Non-aggregate impacts of EP

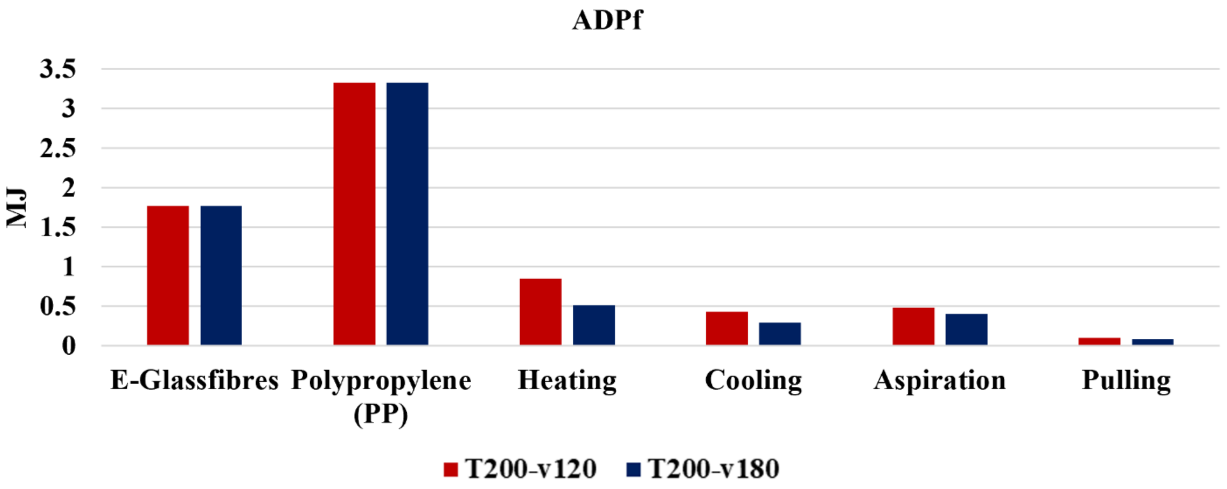

Fig. 8. Non-aggregate impacts of ADPf

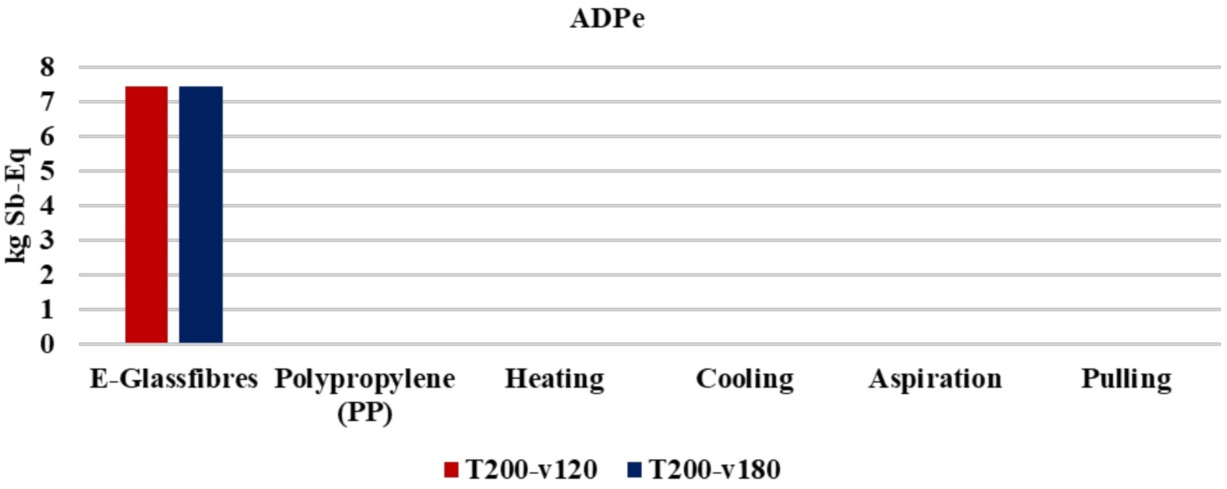

Fig. 9. Non-aggregate impacts of ADPe

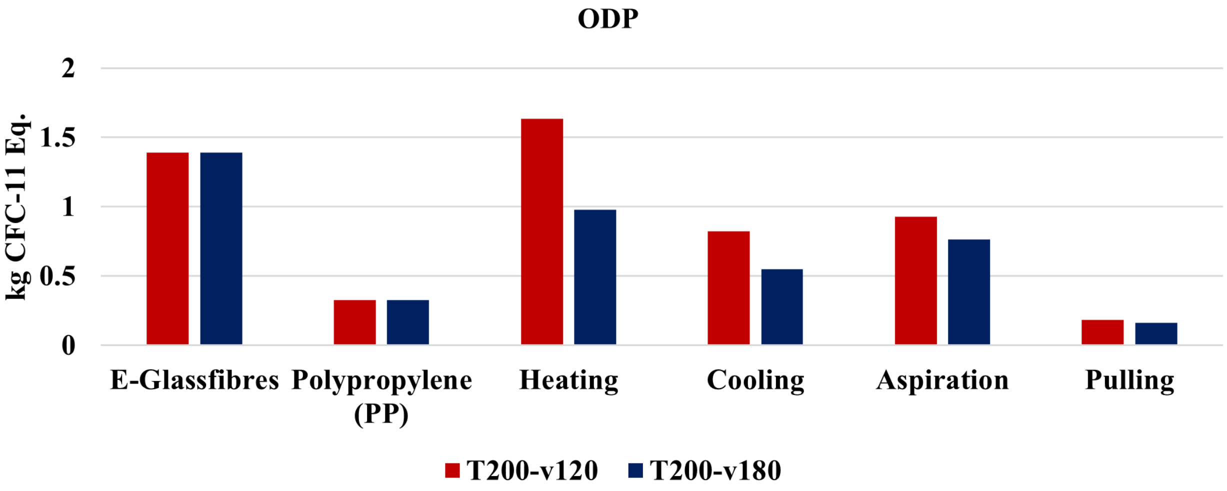

Fig. 10. Non-aggregate impacts of ODP

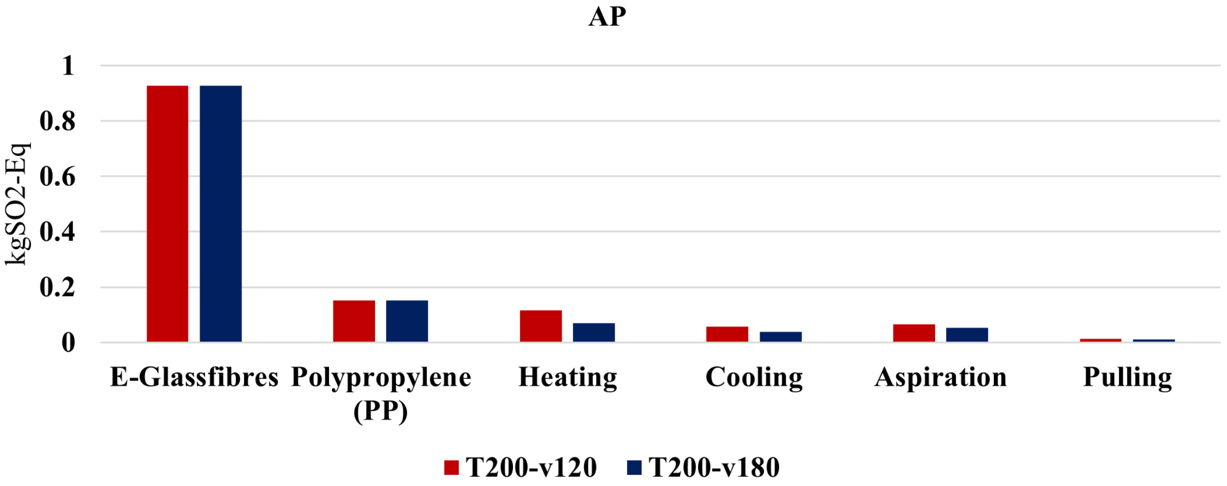

Fig. 11. Non-aggregate impacts of AP

ADPe is almost entirely dominated by E-glass fibers, which account for more than 99 percent of the total impact in both scenarios. As a result, process optimization by varying the tensile speed has a negligible effect on this category, and any significant reduction would require material-level interventions, such as sourcing alternative fibers, substituting the material, or improving the glass fiber manufacturing process. POCP and AP are also primarily driven by material production, with E-glass and polypropylene together contributing more than 80 % of the total impact. Thus, the reduction achieved at v180 is moderate and mainly attributable to decreased energy demand from heating and auxiliary systems. Regarding GWP, the contribution from process energy is more significant (approximately 30-40%), resulting in a more pronounced reduction as drive speed increases. Similarly, the same trend is observed for EP, where the energy contribution decreases significantly at higher speeds, shifting the dominant contribution toward the material phase. The results show that increasing traction speed improves environmental performance in almost all impact categories by reducing the specific energy demand. However, the contribution analysis indicates that not all environmental burdens can be effectively mitigated solely through process intensification. Categories dominated by upstream material production, such as ADPe and partially ADPf, require material-oriented strategies, while energy-dominated categories mainly benefit from operational optimization and thermal management.

The temperature profiles at the core of the pultruded material, acquired using the mobile thermocouple technique, are shown in Fig. 12. The preheating system allows the strips passing through it to gradually increase in temperature from ambient temperature (25–30 °C). However, the setpoint temperature of 90 °C of pre-heater was not able to provide the heat necessary to bring the temperature of the strips close to the melting point. At the entrance to the heating die (330, vertical line), an increase in the dT/dx slope is observed, consistent with entering a zone of greater heat exchange. The increase becomes marked until it reaches a thermal maximum near the entrance to the constant section (480, dashed line) at the compaction condition.

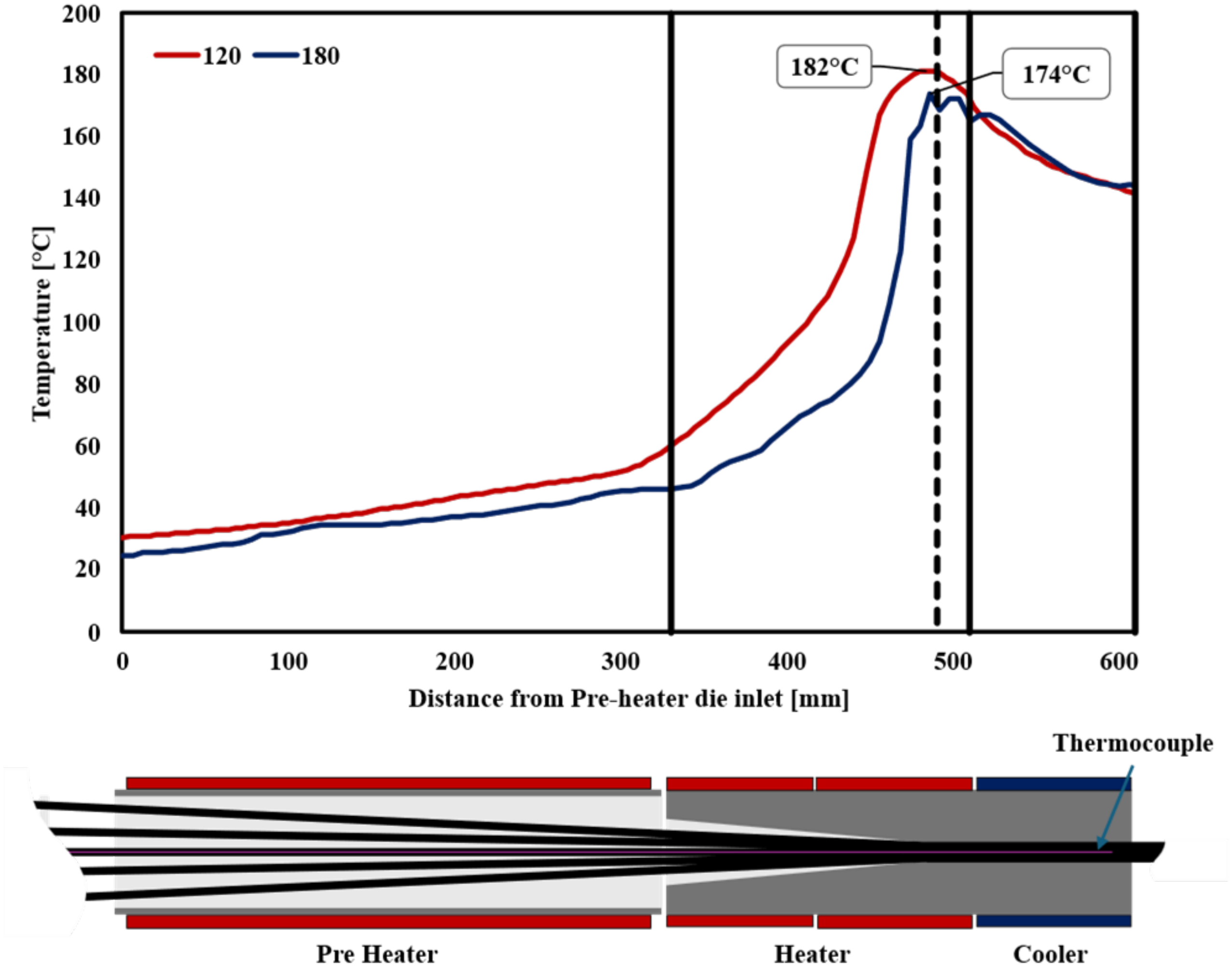

Fig. 12. Temperature at core of pultruded during the process

For the 120 mm/min condition, a temperature of approximately 182 °C is reached, while at 180 mm/min the peak is approximately 174 °C. The difference between the maximums is consistent with the effect of thermal permanence: at lower speeds, the material remains longer in the heated zone and accumulates more heat, approaching the conditions necessary for the softening/melting of PP. In both conditions, the temperatures reached are higher than the melting temperature of the polypropylene in question, thus ensuring a reduction in the viscosity of the PP flow.

The samples subjected to interlaminar shear stress showed large plastic deformations. The maximum load observed in the test at speeds of 120 mm/min and 180 mm/min was approximately 3806 N and 3934 N, respectively. According to ASTM D2344, the maximum interlaminar shear strength of the pultruded composite has a higher value at 120 mm/min of 83.7 ± 9.6 MPa compared to 63.5 ± 17.3 MPa at 180 mm/min, indicating better consolidation and interlaminar adhesion, while the greater variance suggests the presence of more defects. This trend is consistent with the thermal histories measured at the core of the pultruded composite. Indeed, the maximum temperature decreases, as does the residence time above the melting temperature, reflecting a shorter thermal residence time in the heated section. The reduced time above the melt and the shorter compaction time affect polymer flow and pressure-induced redistribution, resulting in lower interlaminar adhesion. Thus, while increased speed improves energy efficiency per unit length, it also introduces a trade-off between consolidation and intensification, which is critical for structural applications.

Conclusions

In conclusion, this study examined the thermoplastic pultrusion of glass fiber-reinforced PP tapes using a laboratory-scale line. A cradle-to-gate LCA analysis was performed to assess the environmental impact of the process. The results showed that the raw material extraction phase is predominant for specific impact categories, such as ADPe and ADPf, while factors such as GWP and ODP are significantly influenced by the process speed. This is a preliminary LCA study to analyze the impacts per sub-process, laying the foundation for future work aimed at optimizing process parameters. The pultruded products obtained were continuous and compact; however, the authors intend to study their microstructure in future work using computed microtomography to identify any connections between process parameters and defects. Despite the surface defects found, the samples taken from the pultruded profile showed significant interlaminar shear strength with higher strength at lower speeds. Although the study is based on primary data, it has several limitations in terms of the number of experimental tests performed and process variables considered. It is important to note that this is a preliminary LCA on the pultrusion process of these materials. Consequently, future developments will involve applying this study to a wide range of process parameters, such as extensive Design of Experiments (DoE) that varies preheating and heating temperatures. This approach aims to establish guidelines for decision support in industry, identifying the optimal trade-off to simultaneously optimize mechanical properties and minimize environmental impact.

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