Materials Science Forum
ISSN: 1662-9752, Vol. 1187, pp 1-15
doi:10.4028/p-JN0Wa7

Submitted: 2026-01-19
Revised: 2026-02-23
Accepted: 2026-02-23
Online: 2026-04-17

Hybrid Hemp/Carbon Fiber Reinforced Composites: Manufacturing, Mechanical Behaviour and Environmental Assessment

DE FAZIO Dario[1,a] *, BIANCHI Iacopo[2,b], BOCCARUSSO Luca[1,c], DURANTE Massimo[1,d], MIGNANELLI Chiara[2,e], PANICO Martina[1,f], PINTO Fulvio[3,g], SIMONCINI Michela[2,h]

[1]Department of Chemical, Materials and Production Engineering (DICMaPI), University of Naples Federico II, P.le V. Tecchio 80, 80125, Napoli, Italy

[2]Department of Industrial Engineering and Mathematical Sciences (DIISM), Università Politecnica delle Marche, Via Brecce Bianche 12, 60131, Ancona, Italy

[3]Material Research Centre, Department of Mechanical Engineering, University of Bath, UK

[a*]dario.defazio@unina.it, [b]i.bianchi@staff.univpm.it, [c]luca.boccarusso@unina.it, [d]mdurante@unina.it, [e]c.mignanelli@pm.univpm.it, [f]martina.panico@unina.it, [g]fp227@bath.ac.uk, [h]m.simoncini@staff.univpm.it

Keywords: Life Cycle Assessment, Flexural Behaviour, Biocomposites.

Abstract. This study analysed the mechanical performances and the environmental sustainability of hybrid hemp/carbon fibre reinforced polymer composites produced adopting different stacking sequences. In this context, three carbon layers were replaced with hemp ones and were positioned either at the mid-plane of the laminate in a symmetric configuration (S sample) and near to the external side of the composite material in an asymmetric configuration (A-HC sample). Additional full carbon sample (CFRP) and hemp sample (HFRP) were manufactured and used as reference materials. The mechanical behaviour of these materials was investigated through flexural, interlaminar shear and low-velocity impact (LVI) tests, and a cradle-to-grave Life Cycle Assessment (LCA) analysis was performed to quantify their environmental impacts in terms of Global Warming Potential (GWP). The experimental results revealed that hemp/carbon hybridisation in composite systems makes it possible to achieve a trade-off between mechanical performances and sustainability. Some of the investigated hybrid configurations exhibited mechanical properties comparable to conventional CFRPs thanks to strength, stiffness and enhanced energy absorption capability which depend on the stacking strategy and the presence of natural fibres that contribute to the damage mitigation. From an environmental perspective, thanks to numerous advantages in the use of hemp fibres, hybrid solutions significantly reduce the global warming potential compared to CFRPs, confirming that hemp/carbon hybridisation represents a promising strategy to balance structural performance and environmental.

Introduction

Fibre-reinforced polymer (FRP) composites are a family of materials that consists of a polymer matrix reinforced with long or short fibrous reinforcement, characterised by unique properties like high specific mechanical properties, chemical resistance and reduced thermal expansion. All these aspects, in conjunction with high levels of tailorability in terms of choice of fibre type, orientation, volume fraction or stacking strategy, have attracted over the last years a growing interest in a wide range of applications such as aerospace, sport, automotive or naval industries [1–9]. The design freedom that characterises this category of materials is not restricted to the choice of fibre's typology, the format, the adoption of a defined production technology or on the possibility of combining all these aspects during the production of the composite material. On the other hand, this freedom is extended to the possibility to introduce within the same composite system, two or more fibre's typologies to produce a fibre hybrid composite (FHC) material with unique mechanical properties [10,11]. The result of the interaction of multiple fibre's typologies is a hybrid composite material where the intrinsic drawbacks of each reinforcement are mitigated because of a synergistic effect that leads to mechanical properties that neither the reinforcements possess [10,11].

Therefore, in light of the possibility to use different fibre's typologies within the same composite system, different strategies of fibre's hybridisations have been investigated over the years [12–15]. More recently, a growing interest of the research community has been directed toward a more environmental sustainability of fibre-reinforced polymer (FRP) composites. In particular, the increasing demand for more sustainable materials, has driven the research toward alternative solutions. In this context, a rising interest has been observed in the use of natural fibres like flax or hemp, and in their use as substitutes for traditional fibres [16,17]. These typologies of reinforcement are typically used for hybridisation with synthetic fibres since they have attracted a significant attention because of their promising potential to reduce the environmental impact of composite materials while maintaining adequate mechanical performances.

To this end, the hybridisation of carbon fibre reinforced plastic (CFRP) composites with natural fibres can mitigate some of the mechanical limitations that affect CFRPs. Thanks to the non-linear behaviour and the high damping characteristics, natural fibres promote different propagation and energy absorption mechanisms when subjected to external loads, reducing the brittle response typical of carbon reinforced composites and improving the energy dissipation efficiency [18–20].

Numerous alternatives of reinforcements can be used in hybridisation of carbon fibre composites in the panorama of natural fibres, however, flax fibres are the most widely investigated in literature where numerous studies have been focalised on impact behaviour, flexural performance, damping and micromechanical modelling to predict the mechanical properties of hybrid composites [16,17]. However, although the advantages of flax fibres, this reinforcement is affected by some drawbacks in terms of high cost, influence of the climatic conditions on the mechanical properties and vulnerability to fungal diseases which increase the storage cost and then the overall cost of the reinforcement [19].

In this scenario, hemp fibres emerge as an attractive alternative thanks to their interesting mechanical properties, low production cost and global availability. Life Cycle Assessment (LCA) studies further highlight the environmental benefit of these fibres such as carbon storage, soil requalification and low nitrate emission [21,22]. Therefore, based on these considerations, the use of hemp fibres in composite materials is increasing and attracting a significant research attention [4–6,23–27]. However, studies that address the mechanical behaviour of hybrid hemp/carbon composites remain limited since these fibres are still rarely used as reinforcement in structural applications.

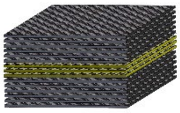
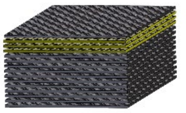
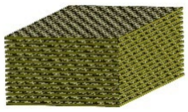
This aspect has further limited the application of LCA analyses to hybrid composite materials since few research studies in literature consider at the same time both the mechanical performances of hybrid composites and the evaluation of their environmental impact through LCA investigations to assess the suitability of these materials for more sustainable industrial applications.

Therefore, the study conducted in the present research work consists of replacing three carbon plies with the same number of hemp ones in a hybrid hemp/carbon composites system and investigate on the mechanical behaviour of these composites in terms of flexural performances and failure analysis combining these results with a LCA analysis to evaluate the trade off between performances and sustainability of this category of hybrid composite materials.

Experimental Procedure

Materials and Laminates Production. For this experimental campaign, the hybrid composite materials were manufactured using a woven hemp fabric with areal density of 160 g/m^2 (supplied by Maeko Srl) and a woven carbon fabric with areal density of 200 g/m^2 (supplied by Toray International Srl). SX 10 epoxy resin (supplied by Mates Srl) was used as matrix to produce hemp/carbon hybrid composite materials. Before the impregnation phase, the natural fabrics were dried in an oven at 60°C and relative humidity of 20% for 12 hours, then a total number of 15 layers (300 x 300 mm^2) were manually impregnated with the epoxy resin using the hand lay-up technique and were placed on a plate mould. The uncured material was sealed in an elastomeric bag under vacuum and was placed in a hydraulic press to allow for the cure. In a first step the composite material was subjected to a pressure of 8 bar at 55 °C for 2 hours, then the cure of the laminate was completed at room temperature under a pressure of 8 bar for 24 hours. Two main hybrid stacking configurations were produced: one by placing the hemp layers in the middle of the laminate (labelled as S sample) and the other by placing the hemp layers on the top of the laminate (labelled as A-HC sample). Full carbon and full hemp laminates were also produced as references (C and H samples respectively) are shown in Table 1.

Table 1. Main laminate's characteristics.

Stacking strategy	**Label**	**Stacking sequence**	**Stacking Schematisation**	**Thickness [mm]**	**Fibre volume fraction [%]**
Carbon laminate	C	$[C_{15}]$		2.81	61.01
Hybrid Sandwich	S	$[C_6H_3C_6]$		3.01	55.69
Hybrid Asymmetric	A-HC	$[CH_3C_{11}]$		3.01	55.69
Hemp laminate	H	$[H_{15}]$		3.70	46.33

Mechanical characterisation. On all sample's typologies three point bending tests were performed according to the ASTM D790 standard, using an MTS Exceed E43 universal testing machine equipped with a 50 kN piezoelectric load cell. The tests were performed on a total number of 5 specimens for each sample configuration by adopting the maximum span-to-depth ratio of 60:1 admitted by the ASTM standard to reduce the shear effects. Particular attention was paid to this aspect since the hybrid configurations are characterised by a high number of hemp/carbon interfaces through the thickness, with concrete possibilities of instauration of interlaminar shear phenomena at the interface between hemp and carbon layers. Therefore, in case of CFRP and hybrid composite samples, specimens 210 mm x 13.2 mm and HFRP reference 300 mm x 18.2 mm were tested using a span length of 180 mm and 230 mm respectively. The flexural stress σ_f was then evaluated using the following Eq. 1 [28]:

$$\sigma_f = \left(\frac{3}{2}\frac{PL}{bd^2}\right)\left[1 + 6\left(\frac{D}{L}\right)^2 - 4\left(\frac{d}{L}\right)\left(\frac{D}{L}\right)\right] \quad (1)$$

where P is the load in N, L is the support span in mm, b and d are respectively the width and the thickness of the specimen in mm and D is the deflection of the specimen in proximity of the loading support in mm.

On the basis of what was asserted for the flexural properties of the samples, the shear characteristics were specifically evaluated through additional interlaminar shear strength (ILSS) tests performed on a total number of 5 specimens for each configuration. To this end the same testing machine was used in a short beam three point bending configuration according to the ASTM D2344 standard. All tests were carried out using a span-to-depth ratio of 5:1 to promote the shear effect in place of the flexural one, then samples 40 mm x 15 mm were tested and the shear stress τ was evaluated as follow (Eq. 2) [29]:

$$\tau = 0.75\ \frac{P}{bd} \tag{2}$$

The impact properties of the laminates were evaluated using a homemade falling drop weight tower equipped with an impactor tip 16 mm in diameter and an impactor mass of 2.66 kg. The impact machine is further equipped with an anti-rebound system that limits the movement of the shuttle after the first impact. The tests were performed according to the ASTM D7136 standard, then 5 specimens for each sample typology 100 mm x 150 mm clamped on their edge were tested at three energy levels (5 J, 10 J and 20 J) obtained by varying the tip height while keeping constant the impactor mass.

The damage was evaluated using non-destructive tests by means of a linear pulse-echo phased array ultrasonic transducer which is characterised by 128 elements with a pitch of 0.5 mm and a central frequency of 5 MHz. An ultrasonic gel was used to connect the array probe to the specimen, ensuring proper ultrasonic wave propagation from the probe to the inspected material. The phased array was further connected to an encoder to enable a C-Scan acquisition. From these tests, two main outputs were obtained: the B-Scan, which enables damage analysis through the cross-section of the specimen by localising defects along the thickness, and the C-Scan, which provides a top-view representation of the specimen, allowing the evaluation of the damage extension and depth.

Life Cycle Assessment analysis. Aiming to evaluate the environmental impacts associated with the different stacking configurations and to identify which one is the most sustainable alternative, the standardized methodology of Life Cycle Assessment, defined by the UNI ISO 14040-14044 standards, was employed. Therefore, the four iterative phases defined in the methodology were followed: (1) Goal and Scope Definition, (2) Life Cycle Inventory, (3) Life Cycle Impact Assessment, (4) Interpretation of results.

The first phase includes the definition of the goal of the study, the Functional Unit (FU), and the system boundaries. The Functional Unit (FU) is defined as the production of a 300 mm x 300 mm composite panel composed by 15 layers. An approach from cradle to grave was considered for the analysis, thus all phases from the raw materials extraction to the end-of-life phase were included within the LCA.

Four scenarios were analysed, corresponding to the four stacking sequences reported in Table 1. Scenario 1 refers to the manufacturing of a fully carbon composite panel (CFRP). Scenario 2 and Scenario 3 consider the manufacturing of hybrid composite panels, adopting the sandwich (S) and asymmetric (A-HC) stacking configurations, respectively.

Scenario 4 refers to the manufacturing of the fully hemp fibre reinforced polymer panel (HFRP)

The analysis included the following phases:

- The production and the transport of reinforcement fibres (either hemp or carbon fibres) and epoxy resin.
- The drying process of hemp fibres in an oven at 60 °C for 12 hours (only for Scenario 2, 3, and 4).
- The production of the mould for the manufacturing process.
- The moulding process, including the consumables needed for the manual impregnation and the energy consumption related to curing and post-curing processes. The process described in the previous paragraph (i.e., moulding using a hydraulic press with a pressure equal to 8 bar and a temperature of 55 °C for 2 hours as curing process and same pressure but room temperature for 24 hours as post-curing process) was considered in the LCA analysis.
- The End Of Life (EoL) of the composite panels. In particular, incineration was considered in all scenarios as it is one of the most common EoL route for composite materials.

The use phase was considered out of the system boundaries. This phase would be greatly influenced by the specific application of the panels; hence, it was not included in the analysis to ensure generality and provide reliable results.

The phases included within the system boundaries are schematically reported in Fig. 1.

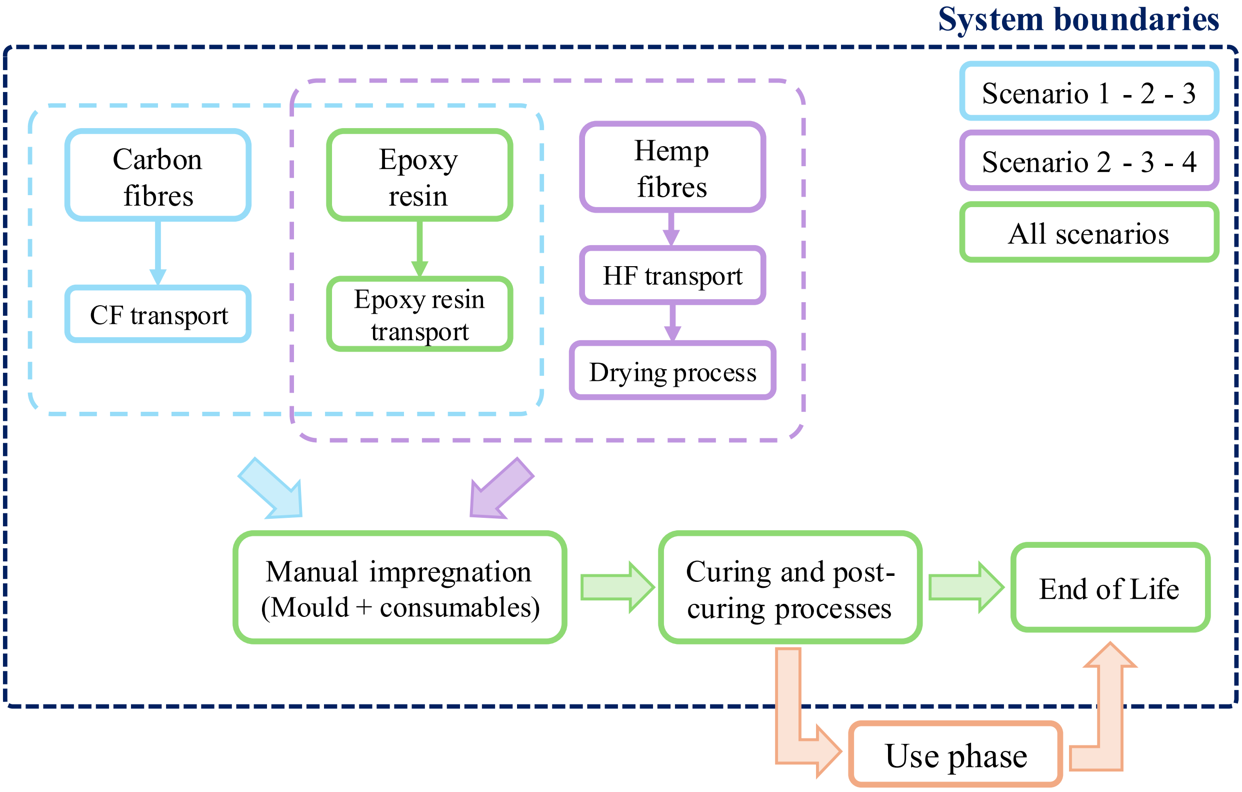


Fig. 1. Schematic representation of system boundaries.

For the Life Cycle Inventory (LCI) phase, both directly measured and secondary data retrieved from literature and Ecoinvent database were used.

Specifically, the weight of the panels of each scenario was calculated on the basis of the defined dimensions (300 mm x 300 mm), the density of each material (1.2 g/cm^3 for the epoxy resin, 1.8 g/cm^3 for the carbon fibres and 1.4 g/cm^3 for the hemp fibres) and the fibre volume fraction equal to 61% and 46% for carbon epoxy and hemp epoxy composite, respectively. Carbon fibres production was modelled according to scientific literature [30], while the dataset related to epoxy resin production provided by the commercial database Ecoinvent was used. As regards the hemp fibres production impacts, relevant scientific literature was considered [31]. The electric energy consumption related to the curing and post-curing processes was estimated on the basis of scientific literature [32], as well as the consumptions related to the consumable materials [33]. The electric energy mix from Italy was considered. The mould weight was estimated based on a CAD model; milling was considered for the mould production and 10% in weight of the mould metal was considered to the removed during the chipping operations. The consumption related to the drying process of hemp fibres was retrieved by literature [33]. Table 2 reports the main LCI input data employed in the LCA analysis.

Table 2. Main LCI input data.

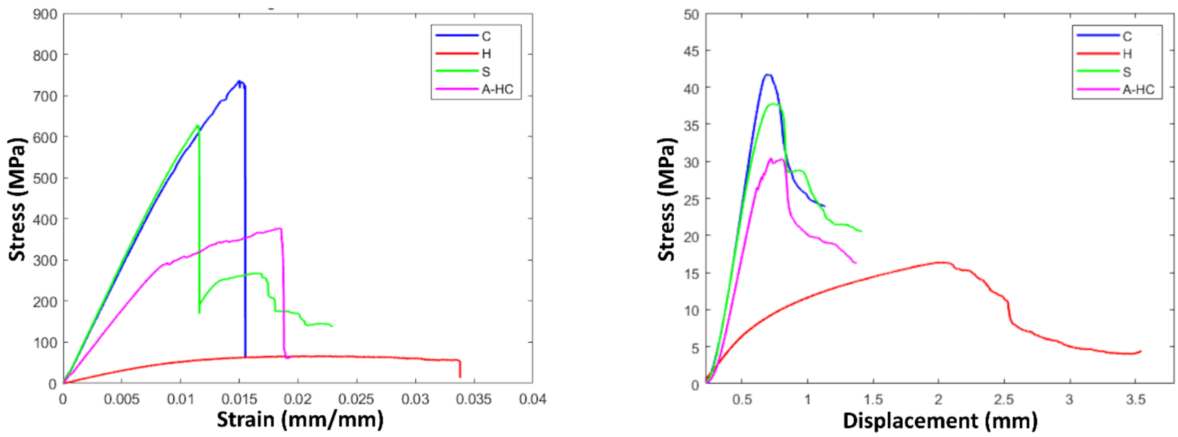
Element	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Unit
Materials					
Carbon Fiber weight	0.27	0.21	0.21	0	kg
Hemp Fiber weight	0	0.04	0.04	0.22	kg
Epoxy resin weight	0.11	0.13	0.13	0.22	kg
Part mass	0.38	0.39	0.39	0.44	kg
Curing process					
Cold press	1.25				kWh
Curing oven	0.05				kWh
Consumables					
Vacuum bag	0.09				kg/m^2
Release agent	0.02				kg/m^2
Sealant tape	0.04				kg/m^2
Mold production					
Mold mass	2.67				kg
Aluminium removed by milling	0.267				kg
Mold service life	750				cycles
Fibers drying					
Energy use	0.75				kWh/ kg

From Table 2 it can be seen that the weight of the materials is the same for Scenario 2 and Scenario 3. This is due to the fact that the two scenarios involve the same total number of hemp and carbon layers, differing only in the stacking sequence. Energy, consumables use and mould production are the same for all the considered scenarios. In fact, the scenarios mainly differ in terms of raw materials and any material-specific processes (e.g., drying applied only to hemp fibres).

SimaPro software was used to model the scenarios and to obtain LCA results. In particular, the environmental impacts were evaluated in terms of Global Warming Potential (GWP, IPCC methodology). GWP method quantifies the effects of the FU on global warming, and it is expressed in kg of CO_2 eq.

Results and Discussion

Flexural and Interlaminar Shear Strength (ILSS) test results. In Fig. 2a and in Table 3 are reported respectively the typical stress-strain curves and the main flexural properties obtained from the bending tests performed on the configurations under inspection. From the curves it is possible to observe the typical flexural behaviour of a CFRP laminate (C sample), where in the initial loading phase, the laminate responds elastically to the applied load with a linear increase as the deformation progresses. During these conditions no visible signs of damages are detected, however, this behaviour continues until the material reaches a critical point that identify the transition from the elastic region to the damage propagation. From this point, internal cracks are generated on the compressive side of the laminate and propagate within the thickness of the specimen as the applied deformation increases. The internal damage is responsible for the reduction of the load-carrying capability with a sharp load drop when the failure occurs.



a) **b)**

Fig. 2. Typical flexural stress-strain curves (a) and Typical ILSS stress-displacement curves for each sample configuration under inspection (b).

Table 3. Main results of flexural and ILSS tests.

	Flexural strength [MPa]		Flexural Modulus [GPa]		Shear Strength [MPa]	
	Mean value	**St. dev.**	**Mean value**	**St. dev.**	**Mean value**	**St. dev.**
CFRP	736.70	45.00	56.42	4.64	41.72	3.16
HFRP	64.85	2.34	6.18	0.25	16.37	0.45
S	627.50	22.80	58.57	4.38	37.78	1.84
A-HC	375.50	12.54	34.79	0.75	29.37	2.61

On the other hand, focusing the attention on the flexural behaviour of the hemp reference (H sample in Fig. 2a), it is possible to assess that this material reveals a pseudo-plastic behaviour if compared to the CFRP laminate. This aspect is typical of natural fibre composites since the internal architecture that characterises the natural reinforcement influence the mechanical behaviour of this category of composite materials [34,35]. Based on these considerations, the H sample showed the lowest value of the elastic modulus (6.18 GPa) and flexural strength (64.85 MPa), then respectively a reduction of almost 87.9% and 91.2% in comparison with the CFRP reference.

Looking at the hybrid configurations, it is possible to point out that the position of the natural fibre layers plays a fundamental role in the mechanical properties of the laminate. The presence of hemp layers influences the failure mode of the hybrid composite because of the difference in the flexural properties of each material and its relative position within the thickness of the laminate. The flexural response of the sandwich configuration (S sample in Fig. 2a), in which the natural fibre layers are placed in the middle plane of the laminate, highlights the effect of the hybridisation, as the presence of natural fibres alters the mechanical properties and the failure mode typical of a CFRP material. This hybrid configuration revealed a pure elastic response, with a flexural modulus comparable to that of fully carbon composite (58.57 GPa), reaching a flexural strength of approximately 627.5 MPa (-14.8% compared to the CFRP reference). This flexural behaviour can be attributed to the position of the natural fibres along the mid-plane of the laminate, which preserves the elastic properties of the hybrid laminate, as confirmed by the similar flexural modulus. However, at peak load, failure is initiated by crack propagation in the compressive region of the laminate and the hemp/carbon interface. This aspect leads to conclude that the hybridisation introduces multiple fracture and damage propagation mechanisms linked to the mechanical properties mismatch between natural and synthetic fibres.

The flexural response of the asymmetric configuration revealed (A-HC sample in Fig. 2a), as well as for the S configuration, a linear trend of the flexural curve along the initial loading phase testifying a good interaction between hemp and carbon fibres. However, unlike the other hybrid configuration, this material does not exhibit a sharp drop of the stress as indicator of the failure of the sample, on the other hand it revealed a large deformation after a threshold value of the elastic region due to the higher strain at failure that characterises hemp fibres. In this region the damage of the material starts and propagates within the material at the interface between hemp and carbon fibres revealing a global reduction of the flexural properties in comparison with the CFRP reference and S sample (-38.3% and -40.6% respectively in case of the flexural modulus and -49% and -40.1% in case of flexural stress).

The ILSS tests revealed the shear response of all samples investigated. In Fig. 2b are reported the main results where it is possible to observe that both the hybrid configurations are characterised by shear properties similar to that of the carbon reference. However, the A-HC hybrid sample, showed a reduction of the maximum shear strength of almost 29.6% in comparison to the CFRP laminate. As it is possible to observe from the curves (Fig. 2b), the A-HC sample is characterised by a double peak before the failure of the specimen that is associated to a delamination at the interface between hemp and carbon layers. This aspect is in line with the results obtained from the flexural tests where the main failure mechanism is associated to hemp layers deformation and delamination at natural/synthetic fibres interface.

Then, based on these observations, it is possible to point out that the hybridisation of carbon fibres with hemp ones can tailor the mechanical properties of this category of materials by combining the brittle behaviour of carbon fibres with the ductile behaviour of hemp ones. It is possible to design the flexural modulus of a hybrid composite material by placing hemp fibres along the thickness of the laminate, more in detail the modulus can be close to that of pure carbon using hemp fibres as core material in a sandwich strategy or can be reduced by placing these natural fibres in an asymmetric configuration.

Low Velocity Impact (LVI) test results. In Fig. 3 are reported the representative impact curves in terms of impact force versus displacement of each configuration subjected to 10 J impact. In this figure are further reported the corresponding results of the C-Scan analysis performed on each sample typology tested at 10 J impact energy. The results of LVI at 5 J and 10 J, highlights that the carbon reference (C sample) is characterised by an elastic behaviour since the restricted area in the force-displacement suggests that large part of the impact energy returned to the impactor during the rebound.

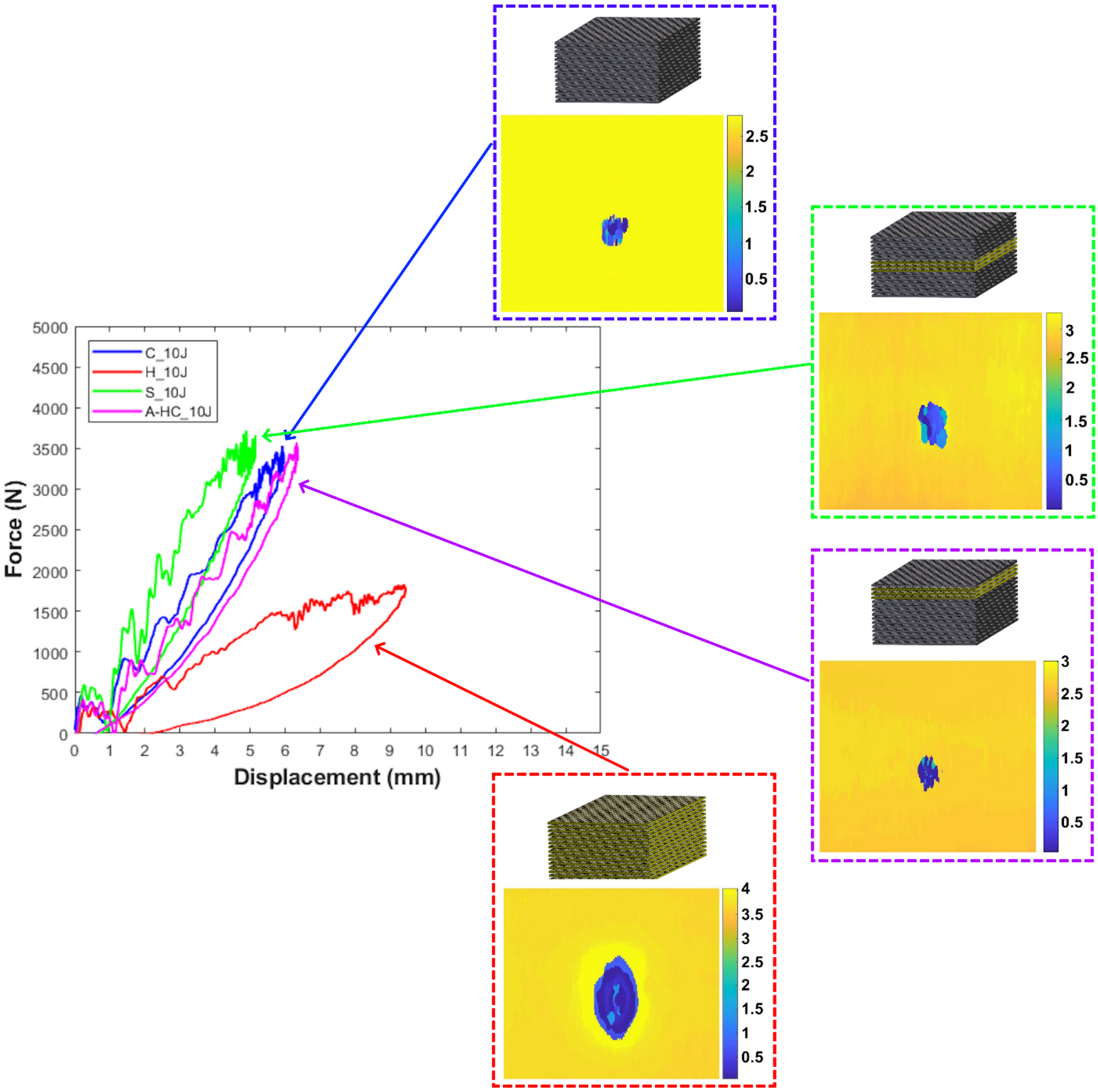


Fig. 3. Force vs displacement curves at 10 J impact energy and C-Scan of the damaged area localisation and extension of each sample configuration.

Table 4. Main results of LVI impact and C-Scan non-destructive tests.

	Energy Level [J]	**Effective Impact Energy E_i [J]**	**Abs. Energy E_a [J]**		**RC [J/J]**		**Damaged Area [mm^2]**	
			Mean value	**St. dev.**	**Mean value**	**St. dev.**	**Mean value**	**St. dev.**
CFRP	5	4.998	0.6250	0.0431	0.8749	0.0086	53.00	17.64
	10	9.995	2.5390	0.3078	0.7460	0.0308	218.10	53.13
	20	19.991	13.3530	2.3052	0.3320	0.1153	469.90	32.29
HFRP	5	4.998	1.8980	0.1107	0.6202	0.0221	110.10	59.44
	10	9.995	5.7350	0.3265	0.4262	0.0327	843.50	702.68
	20	19.991	14.9210	0.9700	0.2536	0.0485	3130.70	675.63
S	5	4.998	0.8010	0.0529	0.8397	0.0106	99.20	29.12
	10	9.995	3.6960	0.1514	0.6302	0.0152	439.90	87.91
	20	19.991	14.3950	0.5362	0.2799	0.0268	680.50	74.23
A-HC	5	4.998	0.5440	0.1217	0.8912	0.0243	8.20	1.26
	10	9.995	2.6590	0.2934	0.7340	0.0294	129.20	16.84
	20	19.991	12.5630	0.4345	0.3716	0.0217	422.50	19.74

This aspect is further supported by the results in Table 4 where the absorbed energy (E_a) corresponds to the 12.5% and 25.4% of the impact energy (5 J and 10 J respectively). The same conclusions can be drawn looking at the return coefficient (RC), which value, ranging between 0 and 1, represents the fraction of the impact energy absorbed by the laminate and it is defined as the ratio between the difference between the impact and the absorbed energies and the prescribed impact one. This coefficient in both cases is 0.87 and 0.74 (5 J and 10 J respectively) meaning that large part of the impact energy returned to the impactor tip. In case of impact energy of 20 J, it was observed a sharp load drop that corresponds to the initiation and propagation of internal damages in proximity of the impact zone. These observations can be further corroborated by the internal damage analysis where the impact event performed at 20 J leads to a damaged area that is more than seven time larger than that obtained from the impact event at 5 J (Table 4). This aspect confirms the brittle behaviour of the pure carbon laminate.

Compared to the C reference, the full hemp laminate (H sample) revealed a pseudo-ductile behaviour since the value of the peak force is the lowest for all the impact energies (- 36.5%, -48.1% and -57.4% respectively in case of 5 J, 10 J and 20 J) and the maximum displacement in correspondence of the maximum impact force is the highest. This behaviour can be attributed to the high damping properties and to the high energy absorbing capability of these natural fibres. These assertions are corroborated by the RC coefficient values which, among the configurations analysed, are always the lowest in all impact conditions (Table 4). The combination of these aspects leads to a larger damaged area in comparison with the CFRP reference, resulting in an increase in the damaged area that is almost double and three times respectively in case of 5 J and 10 J impact energies up to more than five times in case of 20 J impact energy.

The impact tests performed on the S hybrid configuration, revealed a damage extension that increase with the increase of the impact energy (Table 4). The impact curves at 10 J revealed that the presence of hemp layers in the midplane of the laminate do not influence the overall elasticity of the hybrid composite since the material follow a linear trend similar to that of the CFRP reference configuration (Fig. 3). What observed from the impact curves is further supported by the return coefficient (Table 4) that for all impact energies almost corresponds to the value observed in case of the pure carbon laminate.

The C-scan analysis confirmed the presence of internal delamination as consequence of the impact event, that in case of impact energies of 5 J are confined to the upper side of the laminate (the side of the laminate in contact with the indenter tip) at the interface between hemp and carbon layers with an increase of the damaged area of almost 87% compared to the C reference. In case of impact energy of 10 J, the damaged area is almost double than that of the carbon laminate because the damage propagated deeper the material and cracks grew within the laminate involving the lower interface. At 20 J the increase in the damage extension is limited to around 40%, however, severe damages involved the carbon fibres in the tensile region, leading to the total failure of the material. In all cases, the S hybrid configuration revealed an improvement in the absorbed energy linked to the presence of the hemp layers, indeed in case of impact energy of 5 J, 10 J and 20 J the absorbed energy respectively increased of almost +28.2%, +45.6% and +7.8% in comparison with the CFRP reference.

When the hemp layers are positioned on the external side of the hybrid laminate in an asymmetric configuration (A-HC sample), the laminate exhibits a different impact behaviour. More in detail, the presence of hemp layers on the compressive region, then a pseudo-ductile material in correspondence of the impact location, allows for a greater deformation of the area close to the contact zone, enabling a better energy transfer between the impactor tip and the laminate. This aspect is reflected in an increased absorbed impact energy due to the deformation of hemp layers that, in conjunction with the high damping properties of these fibres, led to a reduced damage extension. These results are confirmed by the RC coefficient (Table 4) that for all the impact energies is always the highest among all the configurations and by the damaged area that is always lower than that of the CFRP reference (damaged area reduction of approximately -40.8%, -10.1% respectively in case of 10 J and 20 J impact energies).

Therefore, from the results observed in the symmetric and asymmetric configurations, it is possible to conclude that the presence of hemp layers and the relative position within the thickness of the laminate, influences the impact behaviour of hybrid composites allowing for different energy dissipation mechanisms that lead to different damage extension.

Table 5 and Fig. 4 report the LCA results of all the analysed scenarios, obtained in terms of GWP. In particular, the contributions to total impacts of each phase are shown.

Scenario 1 results as the most impactful one (14.22 kg CO_2 eq), while Scenario 4 is the most sustainable alternative (3.36 kg CO_2 eq). Scenario 2 and Scenario 3 are placed in an intermediate level, with the same ecological footprint (12.05 kg CO_2 eq). The high carbon footprint of Scenario 1 is strongly related to the impacts of carbon fibres; this reinforcement is characterised by high unitary impacts (i.e., 39.9 kg CO_2 eq per kg) and their use accounts for the majority of the scenario impacts. On the other hand, Scenario 4 presents low environmental impacts due to the high sustainability of hemp fibres (i.e., 0.531 kg of CO_2 eq per kg). Even though hemp fibres require a drying phase before moulding, from a sustainability perspective, this phase is almost negligible. This shows how natural fibres represent a much more impactful solution with respect to synthetic ones. The resin contribution to the total impacts is generally low; the highest percentage contribution of the resin is obtained in Scenario 4, due to the higher quantity of epoxy resin with respect to the other scenarios. This is related to the fibres volume fraction which is lower for hemp reinforced composites with respect to those reinforced with carbon fibres. The End of Life phase presents limited contributions for all scenarios and the kg of CO_2 eq associated are similar: the highest value is reached in Scenario 4 due to the weight of the panel which is higher than those of the other scenarios.

It can be observed that Scenario 2 and Scenario 3 present the same environmental impacts; this is related to the same number of carbon plies (12 layers) and hemp ones (3 layers) which involves in the same weight of each material and, subsequently, in the same kg of CO_2 eq produced. Indeed, these two scenarios provide good reduction in impacts with respect to scenario 1 as part of the CFRP layers are replaced with a much more sustainable natural alternative.

The curing processes and consumable materials production give the same contribution to the total impacts of all scenarios, since the input data related to the energy consumption and the quantity of consumables are the same for all of them. In fact, all scenarios are characterised by the same resin and the same curing cycle is considered; hence, despite the differences in stacking sequences, the manufacturing processes are associated with the same carbon footprint in all scenarios. Similar considerations apply to the use of consumables, which mainly depends on part dimensions. Since the panels considered in the different scenarios do not significantly differ in terms of geometry (except for minor variations in thickness) the use of consumable materials can be assumed to be the same for all scenarios.

The production of the mould makes negligible contribution to the total footprint of all the analysed scenarios. This is due to the high number of moulding cycles that a mould can withstand before considering repairing or replacement.

The end-of-life phase was modelled considering incineration and leads to limited impacts (i.e., 0.9-1 kg CO_2 eq). No energy recovery credits were considered in the analysis in order to avoid additional uncertainty related to recovery efficiency and allocation procedures. Literature shows that including energy recovery generally leads to a limited reduction in Global Warming Potential, with comparable magnitudes for synthetic and bio-based systems [36,37]. Reported impacts for incineration with energy recovery are approximately 2 kg CO_2 eq/kg for synthetic composites and bio-based composites. Therefore, the results provided in this study are not expected to significantly change with the inclusion of generic recovery credits. Given the recent focus on EoL of composites, a more accurate quantification could be interesting for future studies, including measured recovery efficiency and different recycling technologies investigation.

Table 5. LCA results in terms of GWP (kg CO_2 eq).

Phase	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Unit
Total	14.22	12.05	12.05	3.36	
Carbon Fiber	11.73	9.38	9.38	0	
Hemp Fiber	0	0.03	0.03	0.13	
Resin	0.58	0.69	0.69	1.11	
Fiber Drying	0	0.017	0.017	0.08	kg CO_2 eq
Consumables	0.32	0.32	0.32	0.32	
Mold	0.007	0.007	0.007	0.007	
Curing	0.67	0.67	0.67	0.67	
EoL	0.91	0.93	0.93	1.00	

Although Scenario 4 proved to be the most sustainable, it does not achieve the best mechanical properties.

For load-bearing structural applications, fully bio-based composites may not always represent the optimal solution. In fact, to obtain bio-based components with mechanical performance comparable to synthetic composites, increased thickness and consequently higher mass may be required; therefore, the relative environmental convenience of the different scenarios may change depending on the structural requirements associated with the functional unit. In the present study, the goal was to compare components with the same geometry, without defining structural requirements, to assess the effects of fibre substitution. In this case, bio-based and hybrid composites demonstrated great potential from a sustainability perspective. Future work should integrate mechanical performance directly into the LCA, using mechanical properties as part of the functional unit definition. This will allow for simultaneously include environmental impacts and mechanical performance in the same analysis, providing a multi decision criteria model for industrial applications.

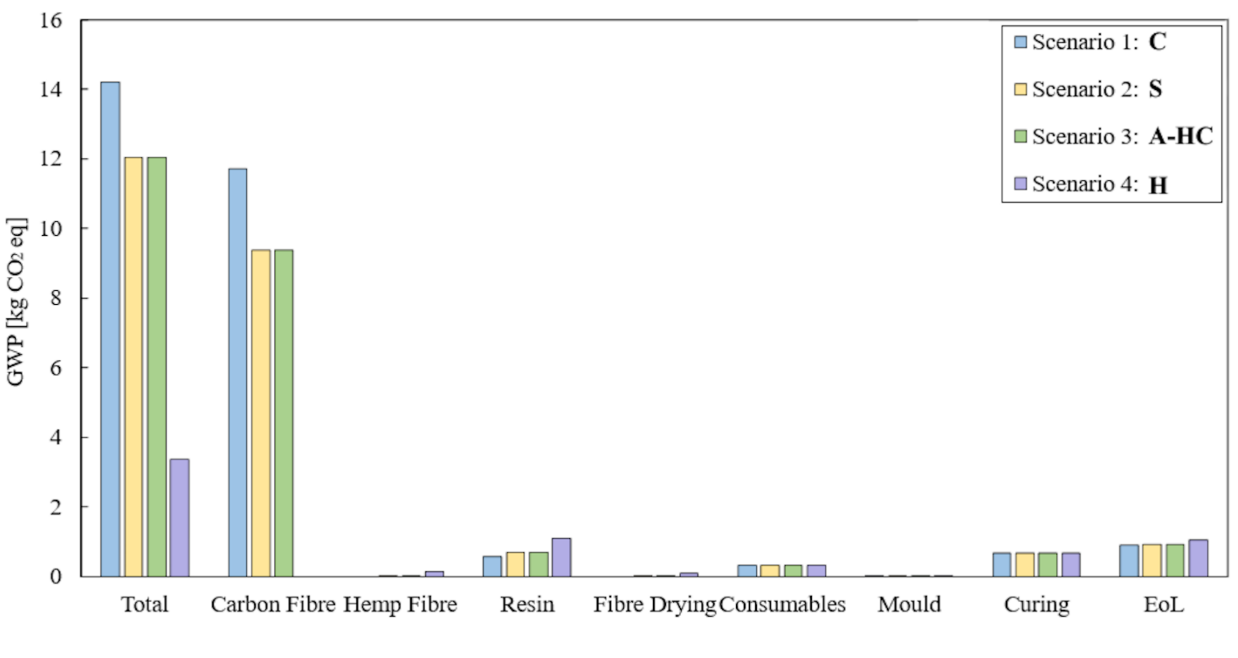


Fig. 4. GWP results of the analysed scenarios.

Conclusions

In the present research work, the effect of the introduction of hemp fibres was investigated in hybrid composite systems by adopting different stacking strategies, and further LCA analysis were performed to evaluate the environmental impact and the sustainability of the different configuration produced, aiming to identifying the most suitable solution. In a first phase of the experimentations, it was assessed the influence of the position of natural fibre's reinforcement within the laminate's thickness on the mechanical performances of the hybrid system and subsequently, the environmental impact of each sample configuration under inspection.

It was observed that the introduction of three hemp layers in place of carbon ones significantly influence the mechanical response and the environmental impact of composite materials, with effects on the mechanical performances that are function of the stacking strategies. When hemp layers are positioned close to the neutral axis (S sample) the flexural stiffness remain comparable to that of the C reference, however, a moderate reduction in the flexural strength (-14.8%) was observed. On the other hand, the asymmetric configuration (A_HC sample), thanks to the ductile behaviour and the high damping capability of natural fibres, resulting in enhanced energy absorption and improved impact damage tolerance (reduction of the damaged area approximately 40% compared to C reference). Therefore, the results of the mechanical tests confirmed that the natural fibre positioning plays a key role in governing the damage mechanisms particularly with delamination phenomena at the hemp/carbon interfaces.

From the LCA analysis, it was observed that C and H samples represent respectively the most impactful and the most suitable alternative because of the high footprint of carbon fibres and the sustainability of hemp ones (GWP value respectively 39.9 and 0.531 kg of CO_2 eq per kg). The hybrid configurations highlighted a clear contribution in global warming potential with a reduction of this indicator of almost 15.3% compared to the C reference.

Based on the analysis of the results, it can be asserted that the hybridisation of carbon fibres with hemp ones can be considered a promising solution since this category of composite materials can provide a significant environmental benefit compared to the conventional CFRP materials maintaining at the same time satisfying structural performances. Therefore, from the experimental investigations emerged that this combination of characteristics in terms of sustainability and mechanical properties, makes hemp/carbon hybrid composite materials very attractive and valuable from an industrial perspective. However, in light of the results obtained from the LCA analysis where it is highlighted the improved sustainability of hybrid composites compared to CFRPs, possible future research directions may include the use of different matrix typologies characterised by a higher sustainability, or the study of recycling technologies to further allow for the reduction of the environmental footprint of hybrid composites, with the aim of integrating the results into a broader LCA analysis.

Refences

[1] P. Taylor, R.S. Joshi, H. Singh, I. Singh, R.S. Joshi, H. Singh, I. Singh, Modulation-Assisted Drilling of Glass-Fiber-Reinforced Plastics Modulation-Assisted Drilling of Glass-Fiber-Reinforced Plastics, Mater. Manuf. Process. 29 (2014) 37–41.

[2] C.L. Tan, A.I. Azmi, N. Muhammad, Delamination and Surface Roughness Analyses in Drilling Hybrid Carbon/Glass Composite, Mater. Manuf. Process. 31 (2016) 1366–1376.

[3] R. Hsissou, R. Seghiri, Z. Benzekri, M. Hilali, M. Ra, A. Elhar, Polymer composite materials : A comprehensive review, Compos. Struct. 262 (2021) 113640.

[4] D. De Fazio, L. Boccarusso, A. Formisano, A. Viscusi, M. Durante, A Review on the Recycling Technologies of Fibre-Reinforced Plastic (FRP) Materials Used in Industrial Fields, J. Mar. Sci. Eng. 11 (2023) 851.

[5] F. Pinto, L. Boccarusso, D. De Fazio, S. Cuomo, M. Durante, M. Meo, Carbon/hemp bio-hybrid composites: Effects of the stacking sequence on flexural, damping and impact properties, Compos. Struct. 242 (2020) 112148.

[6] L. Boccarusso, F. Pinto, S. Cuomo, D. De Fazio, K. Myronidis, M. Durante, M. Meo, Design, Manufacturing, and Characterization of Hybrid Carbon/Hemp Sandwich Panels, J. Mater. Eng. Perform. 31 (2022) 769–785.

[7] L. Boccarusso, D. De Fazio, K. Myronidis, M. Durante, F. Pinto, Bio - inspired optimisation design strategy of graded hemp core for hybrid carbon / hemp sandwich laminates, Int. J. Adv. Manuf. Technol. (2024).

[8] L. Boccarusso, F. Pinto, K. Myronidis, D. De Fazio, M. Durante, Thin Hybrid Hemp/Carbon Fiber Composites: Manufacturing, Flexural, and Impact Behavior, J. Mater. Eng. Perform. 32 (2023) 3914–3922.

[9] L. Boccarusso, V. Antonucci, I. Bianchi, P. Carlone, L. Donati, A. Langella, G. Parodo, F. Quadrini, L. Raimondi, M.R. Ricciardi, L. Santo, M. Simoncini, L. Sorrentino, F. Tucci, Challenges and Opportunities for Composite Manufacturing from a Sustainable Perspective, in: 2025: pp. 261–306.

[10] F. Rizzo, F. Pinto, M. Meo, Development of multifunctional hybrid metal/carbon composite structures, Compos. Struct. 222 (2019) 110907.

[11] C. Bellini, G. Parodo, W. Polini, L. Sorrentino, Experimental investigation of hydrothermal ageing on single lap bonded CFRP joints, Procedia Struct. Integr. 9 (2018) 101–107.

[12] C. Dong, Uncertainties in flexural strength of carbon/glass fibre reinforced hybrid epoxy composites, Compos. Part B Eng. 98 (2016) 176–181.

[13] Y. Zhong, M. Cheng, X. Zhang, H. Hu, D. Cao, S. Li, Hygrothermal durability of glass and carbon fiber reinforced composites – A comparative study, Compos. Struct. 211 (2019) 134–143.

[14] D.K. Jesthi, R.K. Nayak, Improvement of mechanical properties of hybrid composites through interply rearrangement of glass and carbon woven fabrics for marine application, Compos. Part B Eng. 168 (2019) 467–475.

[15] P. yan Hung, K. tak Lau, L. kwan Cheng, J. Leng, D. Hui, Impact response of hybrid carbon/glass fibre reinforced polymer composites designed for engineering applications, Compos. Part B Eng. 133 (2018) 86–90.

[16] F. Sarasini, J. Tirillò, S. D’Altilia, T. Valente, C. Santulli, F. Touchard, L. Chocinski-Arnault, D. Mellier, L. Lampani, P. Gaudenzi, Damage tolerance of carbon/flax hybrid composites subjected to low velocity impact, Compos. Part B Eng. 91 (2016) 144–153.

[17] M.J. Le Guen, R.H. Newman, A. Fernyhough, G.W. Emms, M.P. Staiger, The damping–modulus relationship in flax–carbon fibre hybrid composites, Compos. Part B Eng. 89 (2016) 27–33.

[18] A. Dér, A. Kaluza, D. Kurle, C. Herrmann, S. Kara, R. Varley, Life Cycle Engineering of Carbon Fibres for Lightweight Structures, Procedia CIRP. 69 (2018) 43–48.

[19] C. Santulli, Mechanical and Impact Damage Analysis on Carbon/Natural Fibers Hybrid Composites: A Review, Materials (Basel). 12 (2019) 517.

[20] J. Flynn, A. Amiri, C. Ulven, Hybridized carbon and flax fiber composites for tailored performance, Mater. Des. 102 (2016) 21–29.

[21] P. Linger, J. Müssig, H. Fischer, J. Kobert, Industrial hemp (Cannabis sativa L.) growing on heavy metal contaminated soil: fibre quality and phytoremediation potential, Ind. Crops Prod. 16 (2002) 33–42.

[22] L. Zampori, G. Dotelli, V. Vernelli, Life cycle assessment of hemp cultivation and use of hemp-based thermal insulator materials in buildings, Environ. Sci. Technol. 47 (2013) 7413–7420.

[23] L. Boccarusso, D. De Fazio, K. Myronidis, M. Durante, F. Pinto, Bio-inspired optimisation design strategy of graded hemp core for hybrid carbon/hemp sandwich laminates, Int. J. Adv. Manuf. Technol. 135 (2024) 2811–2827.

[24] D. De Fazio, L. Boccarusso, A. Formisano, R. Grappa, G. Luciani, F. Branda, M. Durante, Mechanical and Solvothermal Recycling of End-of-Life Carbon Fibre-Reinforced Plastic Products: Process Feasibility and Flexural Performance of Recycled Composites, Polymers (Basel). 17 (2025) 1–16.

[25] M.L. Scutaru, M. Baba, Investigation of the Mechanical Properties of Hybrid Carbon-Hemp Laminated Composites Used as Thermal Insulation for Different Industrial Applications, Adv. Mech. Eng. 6 (2014) 829426.

[26] Satish, B. Singh, International Journal of Technical Innovation in Modern Engineering & Science (IJTIMES) Structural Design of Fuselage, Int. J. Tech. Innov. Mod. Eng. Sci. Impact. 5 (2019) 473–477.

[27] M. Ramesh, C. Deepa, G.R. Arpitha, V. Gopinath, Effect of hybridization on properties of hemp-carbon fibre-reinforced hybrid polymer composites using experimental and finite element analysis, World J. Eng. 16 (2019) 248–259.

[28] ASTM INTERNATIONAL, D790-Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials., Annu. B. ASTM Stand. (2002) 1–12.

[29] ASTM INTERNATIONAL., D2344-C. Materials, Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials, i (2016) 1–8.

[30] A. Forcellese, M. Marconi, M. Simoncini, A. Vita, Life cycle impact assessment of different manufacturing technologies for automotive CFRP components, J. Clean. Prod. 271 (2020) 122677.

[31] A.D. La Rosa, G. Recca, J. Summerscales, A. Latteri, G. Cozzo, G. Cicala, Bio-based versus traditional polymer composites. A life cycle assessment perspective, J. Clean. Prod. 74 (2014) 135–144.

[32] Y.S. Song, J.R. Youn, T.G. Gutowski, Life cycle energy analysis of fiber-reinforced composites, Compos. Part A Appl. Sci. Manuf. 40 (2009) 1257–1265.

[33] I. Bianchi, A. Forcellese, I. Taha, Comparative LCA of fully biobased and synthetic polymer composites accounting for fiber treatment, J. Clean. Prod. 530 (2025) 146846.

[34] L. Boccarusso, L. Carrino, M. Durante, A. Formisano, A. Langella, F. Memola Capece Minutolo, Hemp fabric/epoxy composites manufactured by infusion process: Improvement of fire properties promoted by ammonium polyphosphate, Compos. Part B Eng. 89 (2016) 117–126.

[35] L. Boccarusso, M. Durante, A. Langella, Lightweight hemp/bio-epoxy grid structure manufactured by a new continuous process, Compos. Part B Eng. 146 (2018) 165–175.

[36] F. Meng, E.A. Olivetti, Y. Zhao, J.C. Chang, S.J. Pickering, J. McKechnie, Comparing Life Cycle Energy and Global Warming Potential of Carbon Fiber Composite Recycling Technologies and Waste Management Options, ACS Sustain. Chem. Eng. 6 (2018) 9854–9865.

[37] J. Beigbeder, L. Soccalingame, D. Perrin, J. Bénézet, A. Bergeret, How to manage biocomposites wastes end of life ? A life cycle assessment approach (LCA) focused on polypropylene (PP)/ wood flour and polylactic acid (PLA)/ flax fibres biocomposites, Waste Manag. 83 (2019) 184–193.