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Life cycle assessment of glass fibre versus flax fibre reinforced composite ship hulls

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A comparative Life Cycle Assessment (LCA) was conducted between a recreational ship hull made of flax fibre-reinforced bio-based epoxy resin and a traditional ship hull made of glass fibre-reinforced polyester. Since small fibreglass boats pose an environmental problem after the end of life (EoL), the primary aim of this study was to evaluate the sustainability of the biocomposite material and identify recommendations for the future eco-design of recreational boats. The LCA study was developed according to the ISO 14,040 (ISO 14040, 2006), 14,044 (ISO 14044, 2006) methodology and the OpenLCA 2.0.4 software with the Ecoinvent v.3.9.1 database. Compared to the traditional one, the LCA of the biocomposite ship hull showed positive environmental impacts for all indicators except Terrestrial Ecotoxicity (TETP), which increased by 357% due to the use of fertilisers in flax production. Remarkably, the Global Warning Potential (GWP) decreased by 14%, the Human Toxicity Potential (HTP) diminished by 13%, and the Abiotic Depletion Potential (ADP) related to material resources was reduced by 75%. The sensitivity analysis shows that electricity consumption is the primary environmental impact driver for the FFRB ship hull. Thus, selecting renewable energy sources, such as solar or wind power, can significantly enhance sustainability. It is important to note that these impacts are influenced by the system and boundary conditions considered in the study. It was suggested that the local production of flax fibre and the use of recyclable bio-resin could improve the eco-design of the ship hull.

Keywords LCA, Flax fibre, Biocomposite, Glass fibre, Ship hull

In the recreational boating industry, glass fibres are the predominant reinforcing material used in polymer matrix composites. As a result, small ship hulls are primarily manufactured using polyester resin laminates reinforced with mat-type glass fibre due to their low cost, ease of processing, favourable mechanical properties, and resistance to marine environments[1]. However, their low sustainability and limited recyclability at the end of their life cycle pose a significant environmental challenge[2].

Numerous researchers and professionals have dedicated substantial efforts to developing environmentally friendly composite materials in response to heightened global environmental awareness. Consequently, there is a growing emphasis on utilising natural fibres and bio-based resins as replacements for synthetic fibres and petroleum-derived resins[3,4].

Compared with glass fibre, natural fibres such as flax, fique, jute, and hemp have several advantages, like lower density, biodegradability, good damping properties, and high health safety[5]. Moreover, their specific mechanical properties are comparable to or near those of glass fibre-reinforced polymers[6,7]. Although the marine environment can affect the mechanical properties of Natural Fibre-Reinforced Polymers (NFRP), some works demonstrate that seawater immersion does not cause significant ageing in the mechanical performance of the NFRP[8–11]. Consequently, these biocomposites are mechanically feasible in recreational shipbuilding[12].

Concerning the matrix phase, there is an ongoing effort to identify materials derived from renewable resources to replace the petroleum-based matrices in composite materials[13]. Given the inherent limitations of thermoplastics, notably their high viscosity, there is a significant demand for advancements in the development of thermosetting polymers from renewable sources[4,12].

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Among all the natural fibres, flax fibre is a promising substitute for glass fibres for semi-structural and structural applications[14,15], with a lower environmental impact. Regarding marine applications, flax fibre-reinforced bio-resins have been recently used to manufacture components for sea vessels, such as boat hulls and desks. For instance, Bcomp's ampliTex flax fabrics and plant-based epoxy resins were used by some sustainable boat manufacturers to make ship hulls. The replacement of the carbon- and glass-fibre-reinforced composite parts with flax fibre-reinforced bio-resin led to reduced weight, significantly better vibration damping, and better sound performance[16,17].

From an environmental standpoint, natural fibres are perceived as green materials that can be derived from renewable resources and with production techniques that consume less energy than those for synthetic fibres such as glass or carbon fibres[18]. A Life Cycle Assessment (LCA) is an important tool to measure the environmental impact of a product over its life cycle, from cradle to grave[19]. LCAs are increasingly being incorporated into the design and manufacturing workflows of NFRP composites as a robust methodology for quantifying their environmental footprint relative to synthetic fibre-reinforced composites.

The results of LCA demonstrate that flax fibre composites reduce dependence on non-renewable energy and material sources, decrease pollutant and greenhouse gas emissions, enhance energy recovery, and improve the end-of-life biodegradability of components[20,21]. Besides, flax composites lead to a lighter structure and reduced fuel consumption. However, most studies are related to flax fibre-reinforced thermoplastics for automotive applications[22,23]. Regarding thermosetting resins, the latest developments in the synthesis of high-performance bio-based thermosets promote their faster development, especially oriented towards practical applications[24,25]. LCA studies show significant CO2 and greenhouse gas emission reductions compared with petroleum-based thermosetting resins. Furthermore, resins from biomass sourced as a coproduct or from waste streams of other industrial processes significantly reduce carbon footprint and do not compete with food sources[18,26]. Therefore, the recreational boating industry must integrate LCA studies into its manufacturing processes to produce more sustainable products.

This study conducted a Life Cycle Assessment (LCA) to comprehensively evaluate the environmental impacts of manufacturing a ship hull of a small craft using traditional glass fibre-reinforced polyester through hand lay-up techniques. Alternatively, the same ship hull constructed from flax fibre-reinforced bio-resin via vacuum infusion was analysed from a Cradle-to-Grave perspective. Subsequently, a comparative analysis of eleven impact categories was performed to assess the environmental feasibility of the alternative material and process.

Methodology for life cycle assessment

Scope and goal definition

The present work is a comparative life cycle study to evaluate the main environmental impacts associated with producing a ship hull made of flax-reinforced bio-epoxy resin compared with a glass fibre-reinforced polyester resin composite. The Life Cycle Assessment (LCA) study was developed according to the ISO 14,040 (ISO 14040, 2006) and 14,044 (ISO 14044, 2006) methodologies and the OpenLCA 2.0.4 software with the Ecoinvent v.3.9.1 database.

Functional unit

The functional unit of this study is the composite ship hull required for the manufacturing and operation of a Silennis S020 boat (Fig. 1). The ship hull geometry remains consistent across all scenarios; however, two primary scenarios are analysed:

- A glass fibre-reinforced petrochemical-based resin ship hull.
- A flax fibre-reinforced bio-based resin ship hull.

For each scenario, the production phase was assessed, including material requirements, processing techniques, and related factors. The operational stage is identical for both scenarios, though the energy consumption varies

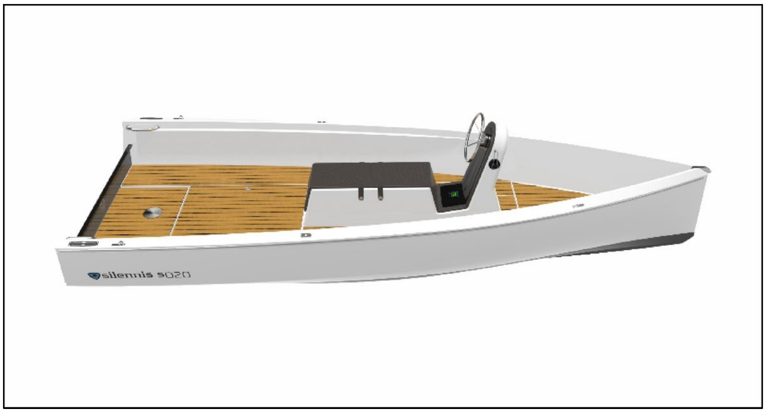


Fig. 1. Silennis S020 boat. License (CC BY 4.0).

depending on the final weight of the hull. For the end-of-life (EoL), landfill was selected as the disposal method to avoid further parameters to be compared.

The main hydrostatic data of the recreational craft are the following: length of the fully loaded waterline, LWL = 4.820 m; the beam of the hull, BH = 1.850 m; draft of the fully loaded waterline, DWL = 0.525 m; and loaded displacement mass, mLDC = 872 kg. Data collection was therefore necessary for all the materials to manufacture the boat under ISO 12215-5:2019 specifications[27]. These rules have a specific section for glass fibre-reinforced polymers (GFRP). However, the mechanical properties of flax fibre-reinforced bio-epoxy (FFRB) were taken from an earlier published work[9]. Thus, the methodology used to determine the final thickness and weight of the respective ship hulls follows the same approach previously published for another Silennis hull model[10]. Based on the design parameters of the Silennis S020 and the mechanical properties of the materials (GFRP and FFRB), the ISO standard defines the minimum required single-skin plating thickness, denoted as t. According to these specifications, the Silennis S020 features a monohull with a $t = 10$ mm thickness. Given the hull area ($A = 31$ m²), the corresponding volume is $V = 0.31$ m³. By applying the density of GFRP ($\rho = 1398$ kg/m³), the calculated weight of the GFRP ship hull is 433.38 kg. For the FFRB hull, the enhanced mechanical properties attributed to the fabric configuration allow for a reduced thickness of $t = 7$ mm. Considering the density of FFRB ($\rho = 1230$ kg/m³), the resulting weight of the FFRB ship hull is 266.91 kg.

System boundaries

The scope of the study is from Cradle-to-Grave in both scenarios, considering the following life stages: obtaining raw materials, manufacturing processes, use, and end of life. Regarding the use life, glass fibre-reinforced polymer (GFRP) small boats typically have a service life ranging from 20 to 30 years[28]. Consequently, the lifespan of the Silennis S020 has been set at 25 years. Based on the company's operational data, an annual usage of 500 h is considered standard, resulting in a total operational duration of 12,500 h over its lifetime. Given that the nominal power of the ship's propeller is 2 kW, the total energy consumption over the estimated lifespan is calculated to be 25,000 kWh. The service life of the FFRB ship hull is assumed to be equivalent, as previous research has demonstrated the mechanical feasibility of FFRB in direct contact with seawater[9]. Conversely, the energy needs depend on the displacement weight, and concerning the ship hull, it is reduced from 433.38 kg made of GFRP to 266.91 kg made of FFRB. The latter values have been considered in the Maxsurf naval design software to obtain the subsequent drag resistances by the Wyman method[29], resulting in $R = 0.86$ kN and $R = 0.78$ kN, respectively. Consequently, the resulting effective power to the cruise speed of the boat (v_s = 4.3 knots) is reduced by 11% using the new displacement weight of the vessel[30]. Therefore, the total energy consumption of the FFRB recreational boat over its operational lifespan is estimated at 22,250 kWh.

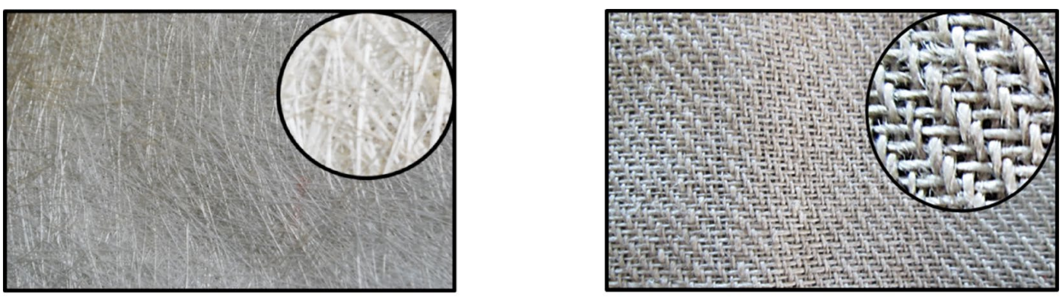
The environmental maintenance impacts have not been considered, as both ship hulls (GFRP and FFRB) will be coated with two layers of the same commercial antifouling paint (Micron 350w from International®) to mitigate biological degradation, photooxidation reactions, and moisture absorption. Moreover, due to the relatively recent introduction of the commercial boat to the market, insufficient data is available to assess maintenance differences during the use phase, and it would be interesting to consider in future work.

In this scenario, it is assumed that the ship hull is landfilled at the end of its life (EoL) for both alternatives (GFRP and FFRB). Landfilling was selected as the disposal method due to the use of fibre-reinforced thermoset composites in both hulls, which present significant challenges for recycling. Additionally, incineration was not considered because it is not environmentally friendly. The growing concerns regarding polymer composite waste have prompted the scientific community to develop advanced recycling techniques[25,31], which may enhance the EoL management of the Silennis S020.

Inventory analysis

Materials and manufacturing

The GFRP ship hull is manufactured by hand lay-up, and the Silennis company provided the quantities of materials used according to the standard specifications. The E-glass fibre reinforcement (Fig. 2a) was from Resinas Castro, S.L., Vigo, Spain, as a mat of 600 g/m^2 in weight. The petroleum-based polyester was CRYSTIC R115PA with a 2% PMEC catalyst from the same provider. Regarding styrene emissions during manufacturing, a 3% wt. was considered in the LCA outputs. The transport of the raw materials from the supplier to the manufacturer in Bizkaia, Spain, was accounted for in the analysis and named *Transport 1*. In addition, the transport of the ship



(a) (b)

Fig. 2. E-glass mat (**a**) and flax fibre (**b**).

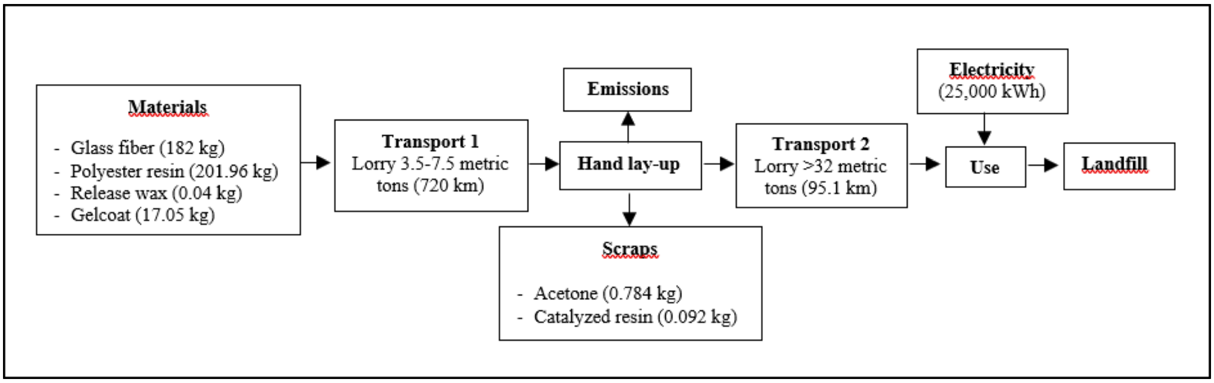


Fig. 3. Data for the life cycle inventory of the GFRP ship hull.

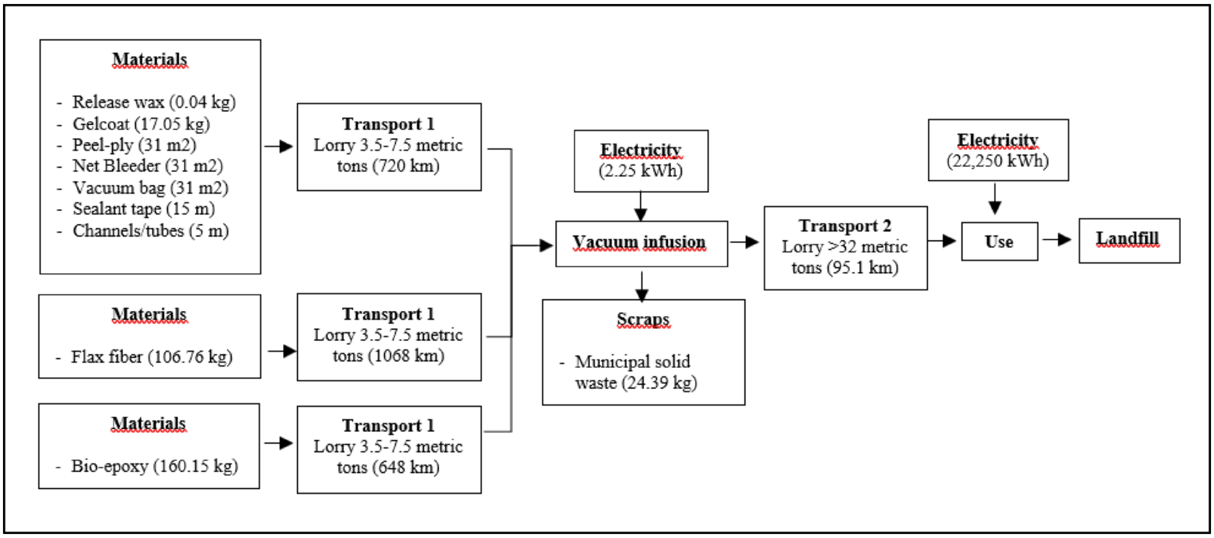


Fig. 4. Data for the life cycle inventory of the FFRB ship hull.

hull from the manufacturer to the assembly company of all the small craft parts was also considered in *Transport 2*. Finally, in the landfill scenario at the end-of-life (EoL), the ship´s transportation to a municipal solid waste treatment facility was excluded as it depends on the shipowner´s location. The data for the inventory of the LCA can be observed in Fig. 3.

Regarding the FFRB ship hull, the vacuum-assisted infusion was considered in the manufacturing process to achieve a more precise thickness and to avoid direct exposure of the operators to resin vapours[3]. Therefore, the energy consumption of the vacuum pump was evaluated in the study, and the scraps after the demolding of the piece were treated as municipal solid waste. The flax fibre reinforcement (Fig. 2b) was supplied by EcoTechnilin, Valliquerville, Francia, as a bi-directional (0/90) woven fabric of 300 g/m^2. The bio-epoxy used was the SuperSap ® 100/1000 Entropy system supplied by Ferrer Dalmau, Barcelona, Spain, which is certified under the U.S. Department of Agriculture (USDA) Certified Biobased Product label program. The mixing ratio of the INF02 curing agent was 100:33 by weight. The quantities of flax fibre, bio-epoxy, and infusion materials were calculated based on previous experiences[10,32] to fulfil the ISO 12215-5:2019 standard[27] and are summarised in Fig. 4. *Transport 1* covers the distance between raw material suppliers and the ship hull manufacturer, and *Transport 2* includes transportation to the assembly facility. Finally, Transport to the landfilling facility is excluded because it depends on the shipowner´s location. The data for the inventory of the FFRB ship hull's life cycle assessment (LCA) is presented in Fig. 4.

Certain materials and equipment have been excluded from the life cycle assessment (LCA) of the manufacturing process for both ship hulls. Specifically, the mould has been omitted as it is assumed to be the same for both cases. Additionally, manual lamination tools, such as brushers and rollers, are reusable, while the vacuum pump used in the infusion process is a multi-purpose device. Furthermore, the assessment excludes the manufacturing facility's infrastructure, including fibre cutting and gas extraction systems.

Considering all the above, the Life Cycle Assessment with OpenLCA and Ecoinvent database was performed by selecting all the raw materials and transports with providers from Europe (RER) and the electric power generation, transmission, and distribution with a provider from Spain (ES). Finally, all the data gathered during the inventory stage was implemented in the software OpenLCA using the Ecoinvent 3.9 database. The final inventory is shown in Table 1:

Environmental impact assessment
For comparative purposes, the CML2016 v.8 methodology was employed due to the data available in the bibliography and literature data on the environmental impacts associated with the yield of the fibres used, glass and flax, and those from the resins involved. This same methodology was applied to calculate the environmental impacts of the production and use during the full life cycle of the ship hulls under investigation. This software version provides up to 11 environmental impacts, enabling an overall analysis and a broader comparative view of the product examined in this research. To validate the results, environmental impact calculations were also

GFRP			
Inputs			
Flow	Amount	Unit	Provider
Electricity, low voltage	25,000	kWh	Electricity voltage transformation from medium to low voltage | electricity, low voltage | Cutoff, U - ES
Glass fibre	182	kg	Glass fibre production | glass fibre | Cutoff, U - RER
Isophthalic acid based unsaturated polyester resin	17.05	kg	Isophthalic acid based unsaturated polyester resin production | isophthalic acid based unsaturated polyester resin | Cutoff, U - RER
Orthophthalic acid based unsaturated polyester resin	201.96	kg	Orthophthalic acid based unsaturated polyester resin production | orthophthalic acid based unsaturated polyester resin | Cutoff, U - RER
Petroleum slack wax	0.04	kg	Petroleum slack wax production, petroleum refinery operation | petroleum slack wax | Cutoff, U - Europe without Switzerland
Transport, freight, lorry 3.5–7.5 metric ton, EURO6	288,756	kg*km	Transport, freight, lorry 3.5–7.5 metric ton, EURO6 | transport, freight, lorry 3.5–7.5 metric ton, EURO6 | Cutoff, U - RER
Transport, freight, lorry > 32 metric ton, EURO6	41214.438	kg*km	Transport, freight, lorry > 32 metric ton, EURO6 | transport, freight, lorry > 32 metric ton, EURO6 | Cutoff, U - RER
Outputs			
GFRP ship hull	1	Item(s)	
Municipal solid waste landfill	Ship hull	kg	Market for municipal solid waste landfill| municipal solid waste landfill| Cutoff, U - ES
Acetone	0.784	kg	Emisions of acetone
Styrene	6.06	kg	Emissions of styrene
FFRB			
Inputs			
Flow	Amount	Unit	Provider
Electricity, low voltage	2.25	kWh	Electricity voltage transformation from medium to low voltage | electricity, low voltage | Cutoff, U - ES
Electricity, low voltage	22,250	kWh	Electricity voltage transformation from medium to low voltage | electricity, low voltage | Cutoff, U - ES
Extrusion, plastic film	3.1	kg	Extrusion, plastic film | extrusion, plastic film | Cutoff, U - RER
Extrusion, plastic film	2.573	kg	Extrusion, plastic film | extrusion, plastic film | Cutoff, U - RER
Extrusion, plastic film	1.767	kg	Extrusion, plastic film | extrusion, plastic film | Cutoff, U - RER
Extrusion, plastic pipes	0.075	kg	Extrusion, plastic pipes | extrusion, plastic pipes | Cutoff, U - RER
Fibre, flax	106.76	kg	Fibre production, flax, retting | fibre, flax | Cutoff, U - RoW
Isophthalic acid based unsaturated polyester resin	17.05	kg	Isophthalic acid based unsaturated polyester resin production | isophthalic acid based unsaturated polyester resin | Cutoff, U - RER
Petroleum slack wax	0.04	kg	Petroleum slack wax production, petroleum refinery operation | petroleum slack wax | Cutoff, U - Europe without Switzerland
Synthetic rubber	0.864	kg	Synthetic rubber production | synthetic rubber | Cutoff, U - RER
Transport, freight, lorry 3.5–7.5 metric ton, EURO6	114019.68	kg*km	Transport, freight, lorry 3.5–7.5 metric ton, EURO6 | transport, freight, lorry 3.5–7.5 metric ton, EURO6 | Cutoff, U - RER
Transport, freight, lorry 3.5–7.5 metric ton, EURO6	103777.2	kg*km	Transport, freight, lorry 3.5–7.5 metric ton, EURO6 | transport, freight, lorry 3.5–7.5 metric ton, EURO6 | Cutoff, U - RER
Transport, freight, lorry 3.5–7.5 metric ton, EURO6	18337.68	kg*km	Transport, freight, lorry 3.5–7.5 metric ton, EURO6 | transport, freight, lorry 3.5–7.5 metric ton, EURO6 | Cutoff, U - RER
Transport, freight, lorry > 32 metric ton, EURO6	25383.141	kg*km	Transport, freight, lorry > 32 metric ton, EURO6 | transport, freight, lorry > 32 metric ton, EURO6 | Cutoff, U - RER
BioResinSuperSab	160.15	kg	
Outputs			
FFRB ship hull	1	Item(s)	
Municipal solid waste landfill	291.3	kg	Market for municipal solid waste landfill | municipal solid waste landfill | Cutoff, U - ES

Table 1. Inventories used for the calculations in OpenLCA software.

performed using alternative methodologies, including ReCiPe 2016 Midpoint H and the CML baseline. The outcomes demonstrated similar magnitudes and trends to those obtained using the CML v4.8 2016 methodology, as presented and discussed below.

Results and discussion

This section presents a comparative analysis of the environmental impacts associated with the production of glass fiber and flax fiber. Additionally, the environmental indicators of petroleum-based polyester resin and the proposed bio-epoxy resin are evaluated. The final section provides a comprehensive cradle-to-grave comparison of GFRP and FFRB ship hulls to assess the environmental advantages of an ecological approach to material selection and design.

Glass fibre versus flax fibre impact assessment

Table 2 compares the impact assessment associated with 1 kg of glass fibre and 1 kg of flax fibre production. In this evaluation, we consider the fibre data from Ecoinvent v.3.9.1 and providers from Europe (RER). The distance of materials transportation from the supplier to the manufacturing company is not considered. The results were obtained by applying the Ecoinvent-CML v4.8 2016 impact assessment method.

Most impact categories are remarkably lower in flax fibre production than glass fibre production. It highlights a 47% reduction in Global Warming Potential (GWP) and 48% and 73% reductions in Freshwater and Marine Ecotoxicity Potentials (FAETP and MAETP). In addition, both Abiotic Depletion Potentials, i.e. those related to fossil fuels (ADP-f) and material resources (ADP-m), are reduced by 68% and 97%, respectively. Ozone Depletion Potential (ODP) and Photochemical Ozone Creation Potential (PCOP) are reduced by 58% and 14%, respectively. This is because the production of flax fibre does not require the consumption of large amounts of non-renewable energy compared to fibreglass[33]. Additionally, the photosynthesis occurring in the plants is considered globally positive for the climate and constitutes a significant advantage of using biomass over fossil resources[20,34].

However, flax production has more than 100% impact on Terrestrial Ecotoxicity (TETP), Eutrophication (EP), and Human Toxicity (HTP) categories, concretely, 3910%, 287% and 162%, respectively. The explanation is that phosphate fertilisers are necessary for growing flax today. They are a major cause of terrestrial toxicity and eutrophication as they are a significant source of nitrogen, phosphorus, and other nutrients. Additionally, they contribute to acid rain and the deterioration of ecosystem health[35–37].

Petroleum-based polyester resin versus SuperSap Entropy resin impact assessment

Table 3 shows the potential environmental impacts associated with 1 tonne of petroleum-based polyester resin and 1 tonne of SuperSap bio-epoxy resin. Orthophthalic acid-based unsaturated polyester resin with a European provider (RER) from Ecoinvent v.3.9.1 was considered as the hand lay-up resin to produce the GFRP ship hull. As opposed to traditional epoxies or polyesters that are composed primarily of petroleum-based materials, SuperSap ® Entropy Resins formulations contain up to 50% of bio-based renewable materials sourced as co-products or from waste streams of other industrial processes, such as wood pulp and bio-fuels production. Consequently, these materials do not compete with food sources or contribute to the displacement of food-based agriculture. By selecting these raw materials and employing green chemistry principles, the company minimizes the environmental impact associated with processing. The environmental impacts of SuperSap® were obtained from Entropy Resins and bibliography[18]. This assessment did not include the transport of the resins from the suppliers to the ship hull manufacturer.

Consequently, the bio-epoxy significantly reduces Freshwater Aquatic Ecotoxicity Potential (FAETP), Human Toxicity Potential (HTP) and Ozone layer Depletion Potential (ODP), concretely, 95%, 92% and 100%, respectively. Furthermore, it decreases the Eutrophication Potential (EP) and Abiotic Depletion Potential related to material resources (ADP-m) by 44% and 58%, respectively. This is because the renewable origin of the bio-resin does not compete with food sources.

Impact category	Units	Glass fibre[a]	Flax fibre[b]
Acidification (AP)	kg SO2-Eq	0.013	0.018
Global warming potential (GWP)	kg CO2-Eq	2.144	1.146
Freshwater aquatic ecotoxicity (FAETP)	kg 1,4-DCB-Eq	1.117	0.583
Marine aquatic ecotoxicity (MAETP)	kg 1,4-DCB-Eq	3460.078	929.235
Terrestrial ecotoxicity (TETP)	kg 1,4-DCB-Eq	0.045	1.798
Abiotic depletion potential: fossil fuels (ADP-f)	MJ	26.615	8.463
Eutrophication (EP)	kg PO4-Eq	0.005	0.019
Human toxicity (HTP)	kg 1,4-DCB-Eq	10.817	28.335
Abiotic depletion potential: metals/minerals (ADP-m)	kg Sb-Eq	2.920E-04	8.412E-06
Ozone layer depletion (ODP)	kg CFC-11-Eq	4.744E-08	2.009E-08
Photochemical oxidant potential (PCOP)	kg ethylene-Eq	7.321E-04	6.329E-04

Table 2. Potential environmental impacts associated with 1 kg of glass fibre and 1 kg of flax fibre production. [a] Environmental impact results from the Ecoinvent v.3.9.1 database.

Impact category	Units	Petroleum-based polyester resin[a]	SuperSap bio-epoxy resin[b]
Acidification (AP)	kg SO2-Eq	13.682	25.440
Global warming potential (GWP)	kg CO2-Eq	3506.773	4079.000
Freshwater aquatic ecotoxicity (FAETP)	kg 1,4-DCB-Eq	1408.703	66.390
Marine aquatic ecotoxicity (MAETP)	kg 1,4-DCB-Eq	2.962E + 06	---
Terrestrial ecotoxicity (TETP)	kg 1,4-DCB-Eq	31.355	228.630
Abiotic depletion potential: fossil fuels (ADP-f)	MJ	7.963E + 04	8.800E + 04
Eutrophication (EP)	kg PO4-Eq	12.351	6.900
Human toxicity (HTP)	kg 1,4-DCB-Eq	6707.867	545.170
Abiotic depletion potential: metals/minerals (ADP-m)	kg Sb-Eq	0.024	0.010
Ozone layer depletion (ODP)	kg CFC-11-Eq	3.858E-04	0.000
Photochemical oxidant potential (PCOP)	kg ethylene-Eq	1.344	1.90

Table 3. Potential environmental impacts associated with 1 tonne of petroleum-based polyester resin and 1 tonne of supersap bio-epoxy resin. [a] Environmental impact results from the Ecoinvent v.3.9.1 database. [b] Environmental impact results from the bibliography[18].

Impact category	Units	GFRP[a]	FFRB[b]
Acidification (AP)	kg SO2-Eq	35.28	32.81
Global warming potential (GWP)	kg CO2-Eq	8549.94	7332.5
Freshwater aquatic ecotoxicity (FAETP)	kg 1,4-DCB-Eq	7252.5	5191.8
Marine aquatic ecotoxicity (MAETP)	kg 1,4-DCB-Eq	2.78E + 07	1.93E + 07
Terrestrial ecotoxicity (TETP)	kg 1,4-DCB-Eq	57.95	265.1
Abiotic depletion potential: fossil fuels (ADP-f)	MJ	1.14E + 05	8.37E + 04
Eutrophication (EP)	kg PO4-Eq	12.56	10.97
Human toxicity (HTP)	kg 1,4-DCB-Eq	1.02E + 04	8881.7
Abiotic depletion potential: metals/minerals (ADP-m)	kg Sb-Eq	0.08	0.02
Ozone layer depletion (ODP)	kg CFC-11-Eq	0.00	0.00
Photochemical oxidant potential (PCOP)	kg ethylene-Eq	2.26	1.7

Table 4. Potential environmental impacts of the GFRP versus FFRB ship Hull. [a] Environmental impact results from the Ecoinvent v.3.9.1 database. [b] Environmental impact results from Ecoinvent v.3.9.1 plus bibliography included in the software OpenLCA.

By contrast, increase of 86% in Acidification Potential (AP), 16% in Global Warming Potential (GWP) and 11% in Abiotic Depletion Potential: fossil fuels (ADP-f) are observed and, especially, a significant drawback is found in the Terrestrial Ecotoxicity Potential category (ΔTETP = + 629%), which may be due to the high percentage (35%wt) of chemical hardener used by SuperSap.

GFRP versus FFRB ship hull impact assessment

Table 4 shows the comparison of the impact assessments associated with the production and life use of the Silennis S020 ship hull, manufactured with glass fibre-reinforced polyester (GFRP) and flax fibre-reinforced bio-epoxy (FFRB). The results were obtained using data from the Ecoinvent v.3.9.1 database and the CML v4.8 2016 impact method. Regarding the FFRB, the environmental impact of the bio-epoxy was added in a new flow in the software OpenLCA, including the corresponding impacts found in literature (Table 3). In addition, as explained in *2.1.2. System Boundaries* section, consideration has been given to the fact that the reduced weight of the FFRB hull will result in lower battery consumption and reduced electrical load during its use life. Finally, the landfill scenario was considered the end-of-life stage in both cases.

Figure 5 facilitates a clearer visual analysis of the results. It demonstrates that, across all environmental impact categories—except for terrestrial ecotoxicity—the ship hull manufactured using flax fibres and bio-based resin exhibits superior environmental performance.

Figure 6 shows the corresponding percentages of variation of the different impact categories associated with both alternatives for manufacturing the ship hull and their consequences on life use. It can be observed that all impact categories are significantly lower in FFRB than in GFRP ship hull except for Terrestrial Ecotoxicity (TETP), which increased a ΔTETP = 357% because of the use of fertilisers in flax production[20,37].

It can be stated that manufacturing the ship hull with FFRB instead of GFRP reduces the compounds responsible for acid rain ΔAP= -7% and Global Warming (ΔGWP= -14%). Regarding the hazardous chemicals' detrimental impact on different natural ecosystems, it is reduced in two of them: freshwater (ΔFAETP= -28%) and marine (ΔMAETP= -31%). The depletion of fossil fuels and material resources is reduced ΔADP-f= -27%

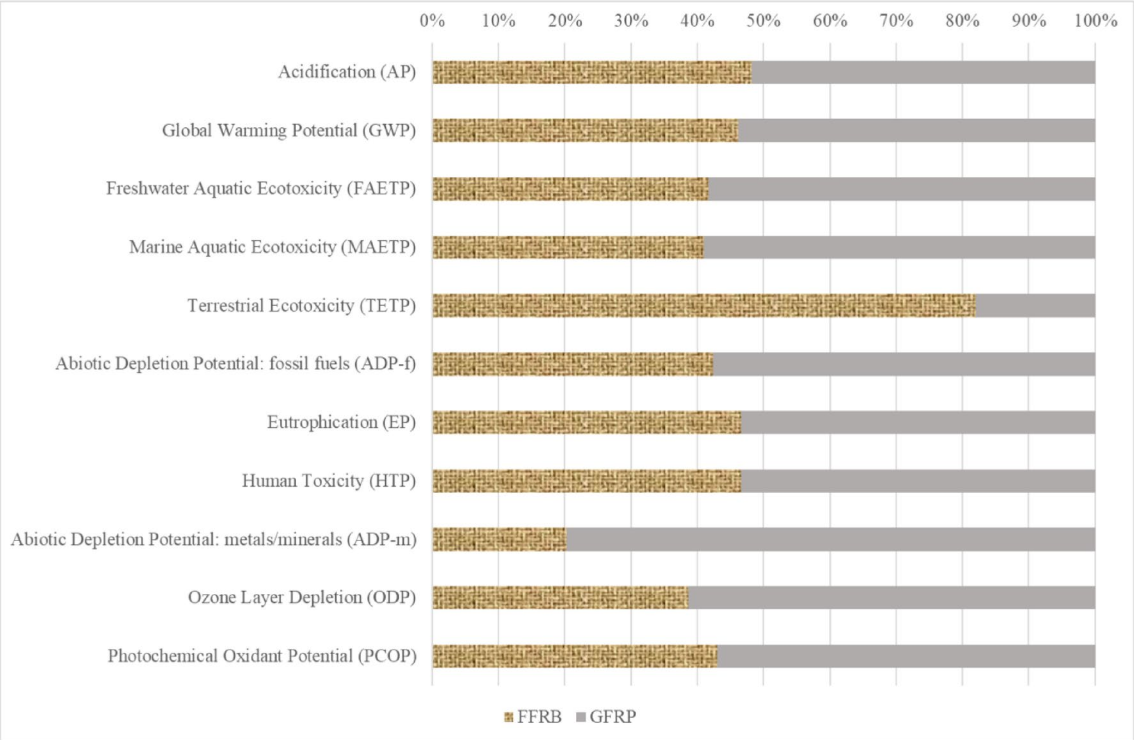


Fig. 5. Environmental impact categories calculated using CML 2016 v4.8 methodology and the corresponding contributions for FFRB versus GFRP ship hull.

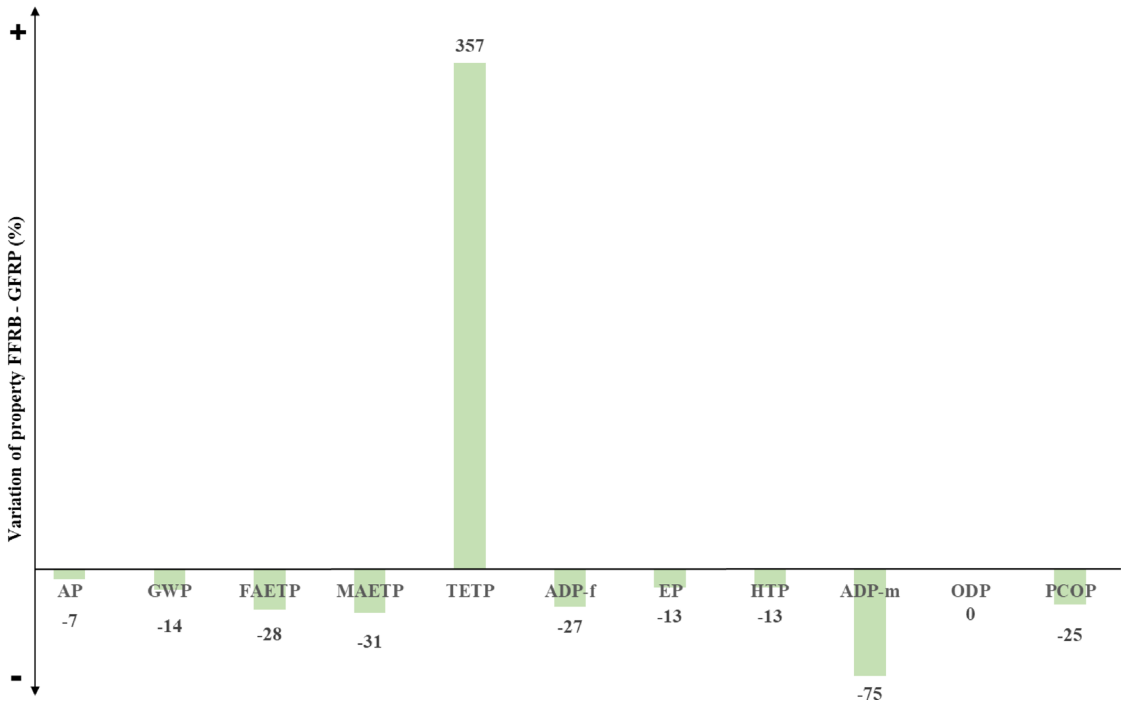


Fig. 6. Percentages of impact category variations associated with manufacturing and life use of the FFRB versus GFRP ship hull.

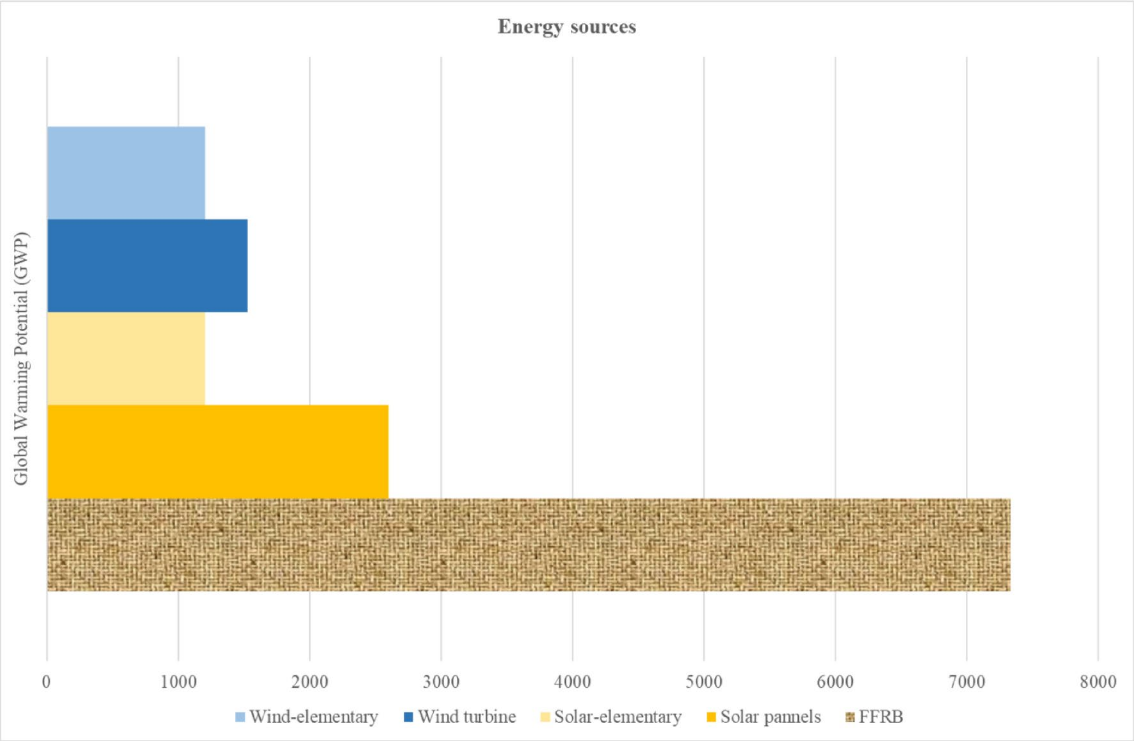


Fig. 7. Environmental impact categories calculated using CML 2016 v4.8 methodology for the corresponding scenarios resembling different energy sources for the FFRB ship hull.

and ΔADP-m= -75%, respectively. Besides, over-fertilization of water and soil is avoided by a ΔEP= -13%, and it diminishes the release of toxic materials to humans (ΔHTP= -13%).

Finally, the FFRB alternative reduces the Photochemical Oxidant Potential (ΔPCOP= -25%), which refers to the presence of volatile organic compounds such as ethane in the air. The damage to the ozone layer is the same in both alternatives (ΔODP = 0%).

Another aspect analysed in the comparative LCA was treating waste at the end of life. The landfill scenario was selected because both ship hulls are manufactured with fibre-reinforced thermoset composites that are difficult to recycle, and the incineration alternative is not environment-friendly. The advantage of the FFRB ship hull lies in its reduced weight (ΔW = −166.47 kg) compared to the GFRP ship hull when transported to a municipal solid waste treatment facility. Such a benefit was excluded from the LCA because it depends on the shipowner´s location, but it would be interesting to consider it with company-specific data.

Future life cycle assessments should consider recent advances in mechanical, thermal, and chemical recycling. Thermal recycling has proven effective in recovering high-quality resources from epoxy resins and synthetic fibres; however, it is associated with high energy consumption[38]. In contrast, mechanical recycling is recognised as the most energy-efficient approach, providing satisfactory material properties[39]. Chemical recycling, while also effective, involves significant costs and poses environmental concerns[31]. Targeted research is required to explore the recycling and reuse of flax fibre-reinforced bio-composites (FFRBs), thereby offering a viable end-of-life (EoL) scenario that contributes to waste reduction and supports the advancement of a circular economy[40], as is being achieved in other sectors such as rail[41] and wind power[42].

Sensitivity analysis for FFBR ship hull

The major contributor to most environmental impact categories is the electricity consumed during the manufacturing and use stages. For instance, for climate change related to the Global Warming Potential (GWP), approximately 80% of the total impact is attributed to electricity consumption and up to 6% is associated with flax fibre production. To assess the influence of energy sources on the results, several scenarios have been analysed, considering four different energy scenarios:

- Electricity generated from Si-based solar panels.
- Solar energy in its elementary form.
- Electricity from wind turbines.
- Electricity from wind in its elementary form.

The results of this analysis are presented in Fig. 7. As indicated by the findings, the environmental impacts assessed in this study are highly dependent on the energy required during the boat use stage. Therefore, selecting an appropriate energy source such as wind or solar-elementary sources can further enhance the environmental benefits.

Conclusions

This paper aimed to deduce whether manufacturing a recreational ship hull with flax fibre-reinforced bio-resin (FFRB) instead of the traditional glass fibre-reinforced polyester (GFRP) is beneficial in terms of environmental impacts. For this, a comparative LCA was performed by comparing materials, manufacturing processes, service life and end-of-life through OpenLCA software and Ecoinvent v.9.3.1 database. Based on the LCA obtained results, one can conclude that:

- The key environmental indicators include a 14% reduction in global warming potential, 27% and 75% decreases in fossil fuel and material resource depletion, respectively, and considerable reductions in toxicity-related categories. These findings underscore the environmental advantages of swapping from synthetic fibre to natural fibre and from a petroleum-based resin to a biobased resin in manufacturing marine fibre-reinforced composite structures such as ship hulls.
- The ship hull manufactured with FFRB by the vacuum infusion process is lighter than those manufactured with GFRP by hand lay-up, thanks to a significant thickness control and the higher specific physical-mechanical properties of the biocomposite. The weight reduction is directly related to drag resistance reduction and, consequently, to power needs, which are reduced by 11%. It is, therefore, estimated that 2,750 kWh are saved over its service life, with a consequent reduction in environmental impact.
- The environmental impacts of flax fibre are generally lower than those of glass fibre, except for the impact indicator associated with fertiliser usage. Promoting sustainable and local agriculture could improve the sustainability of natural fibre.
- The sustainability of the bio-epoxy resin could be further improved by increasing its percentage of renewable materials, concretely to decrease the Terrestrial Ecotoxicity Potential. Alternative recyclable resins should also be considered in future research.
- The overall impact of the FFRB ship hull is considerably lower than the GFRP ship hull in ten of the considered impact categories of the LCA from de Cradle-to-Grave. Reduction percentages are approximately 20%, with notable decreases observed in abiotic depletion related to material resources (metals/minerals) exceeding this reduction threshold.
- The sensitivity analysis highlights that electricity consumption during the manufacturing and use stages is the primary driver of environmental impacts for the FFRB ship hull, with up to 80% of the Climate Change impact attributed to energy use. The analysis of different energy scenarios demonstrates that the choice of energy source significantly influences overall environmental performance. Therefore, adopting renewable energy sources, such as solar or wind power, can further reduce the environmental footprint and enhance sustainability.

Based on the conclusions of the present research work, one could state that FFRB is an eco-friendly material to manufacture the ship hull of small crafts. However, a strategy for end-of-life treatment should be developed to improve the circular economy. New investigations focused on reuse and new recycling techniques would profit from the advantages of natural fibres as reinforcements of composite materials. In this sense, the efforts developing low-viscosity thermoplastics and recyclable bio-thermoset resins are promising avenues of research to promote greater sustainability and the circular economy of FFRB composites.

Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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References

1. Rubino, F., Nisticò, A., Tucci, F. & Carlone, P. Marine application of Fiber reinforced composites: A review. *J. Mar. Sci. Eng.* **8**, 26–54 (2020).
2. Nandakumar, C. G. Environmental impact of non metallic hull ships. *International Conference on Green Technologies (ICGT)* (IEEE, 2012).
3. Torres-Arellano, M., Renteria-Rodríguez, V. & Franco-Urquiza, E. Mechanical properties of Natural-Fiber-Reinforced biobased epoxy resins manufactured by resin infusion process. *Polymers* **12**, 1–17 (2020).
4. Liu, W. et al. Properties of natural fiber-reinforced biobased thermoset biocomposites: Effects of fiber type and resin composition. *Compos. B Eng.* **171**, 87–95 (2019).
5. Akter, M., Uddin, M. H. & Anik, H. R. Plant fiber-reinforced polymer composites: a review on modification, fabrication, properties, and applications. *Polym. Bull.* **81**, 1–85 (2023).
6. Kumar, S., Manna, A. & Dang, R. A review on applications of natural Fiber-Reinforced composites (NFRCs). *Mater. Today*. **50**, 1632–1636 (2021).
7. Kumar, R., Ul Haq, M. I., Raina, A. & Anand, A. Industrial applications of natural fibre-reinforced polymer composites–challenges and opportunities. *Int. J. Sustain. Eng.* **12**, 212–220 (2019).
8. Ramón Valencia, F. et al. Influence of seawater immersion in low energy impact behavior of a novel colombian fique fiber reinforced bio-resin laminate. *DYNA* **82**, 170–177 (2015).
9. Valencia, F. R., Castillo-López, G., Aurrekoetxea, J. & Lopez-Arraiza, A. Fibre–wood laminate biocomposites: seawater immersioneffects on flexural and low energy impact properties. *Polymers* **14**, 4038–4051 (2022).

10. Velasco-Parra, J. A., Valencia, F. R., Lopez-Arraiza, A. & Ramón-Valencia, B. Castillo-López, G. Jute fibre reinforced biocomposite: seawater immersion effects on tensile properties and its application in a ship hull design by finite-element analysis. *Ocean. Eng.* **290**, 1–7 (2023).
11. Mourad, A. I., Idrisi, A. H., Wrage, M. C. & Abdel-Magid, B. M. Long-term durability of thermoset composites in seawater environment. *Compos. B Eng.* **168**, 243–253 (2019).
12. El Hawary, O., Boccarusso, L., Ansell, M. P., Durante, M. & Pinto, F. An overview of natural Fiber composites for marine applications. *J. Mar. Sci. Eng.* **11**, 1–52 (2023).
13. Rosenboom, J., Langer, R. & Traverso, G. Bioplastics for a circular economy. *Nat. Rev. Mater.* **7**, 117–137 (2022).
14. Shah, D. U., Schubel, P. J. & Clifford, M. J. Can flax replace E-glass in structural composites? A small wind turbine blade case study. *Compos. B Eng.* **52**, 172–181 (2013).
15. Yan, L., Chouw, N. & Jayaraman, K. Flax fibre and its composites–A review. *Compos. B Eng.* **56**, 296–317 (2014).
16. https://www.balticyachts.fi/yachts/baltic-68-cafe-racer/
17. https://www.compositesworld.com/news/sicomin-bio-based-resins-used-in-flax-fiber-reinforced-boat-
18. La Rosa, A. D. et al. Bio-based versus traditional polymer composites. A life cycle assessment perspective. *J. Clean. Prod.* **74**, 135–144 (2014).
19. Bjørn, A., Owsianiak, M., Molin, C. & Laurent, A. *Life Cycle Assessment: Theory and Practice* 9–16. (Springer, Berlin/Heidelberg, 2018).
20. Le Duigou, A., Davies, P. & Baley, C. Environmental impact analysis of the production of flax fibres to be used as composite material reinforcement. *J. Biobased Mater. Bio*. **5**, 153–165 (2011).
21. Koronis, G., Silva, A. & Ong, M. Comparison of structural performance and environmental impact of epoxy composites modified by glass and flax fabrics. *J. Compos. Sci.* **6**, 1–16 (2022).
22. Sifiso, J. S., Khoathane, C. & Malwela, T. Driving towards sustainability: A review of natural fiber reinforced polymer composites for eco-friendly automotive light-weighting. *J. Thermoplast Compos. Mater.* **38**, 754–780 (2025).
23. Boland, C. S. et al. Life cycle impacts of natural Fiber composites for automotive applications: effects of renewable energy content and lightweighting. *J. Ind. Ecol.* **20**, 179–189 (2016).
24. Liu, J. et al. Recent development on bio-based thermosetting resins. *J. Polym. Sci.* **59**, 1474–1490 (2021).
25. Liu, J. et al. Advances in sustainable thermosetting resins: from renewable feedstock to high performance and recyclability. *Prog Polym. Sci.* **113**, 1–49 (2021).
26. Shahid, A. T., Silvestre, J. D., Hofmann, M., Garrido, M. & Correia, J. R. Life cycle assessment of an innovative bio-based unsaturated polyester resin and its use in glass fibre reinforced bio-composites produced by vacuum infusion. *J. Clean. Prod.* **441**, 1–13 (2024).
27. ISO 12215-5:2019. Small craft - hull construction and scantlings - Part 5: Design pressures for monohulls, design stresses, scantlings determination.
28. Geraghty, R., Graham-Jones, J., Pemberton, R., Summerscales, J. & Bray, S. Sustainability considerations for end-of-life fibre-reinforced plastic boats. *Reg. Stud. Mar. Sci.* **83**, 1–20 (2025).
29. Bentley Systems. User Manual for Maxsurf Resistance, 1–72. (2024).
30. Lutfi, M. A. et al. Leisure boat concept design: study on the influence of hull form and dimension to increase hydrodynamic performance. *Int. J. Mech. Eng. Robot Res.* **13**, 139–161 (2024).
31. Khalid, M. Y., Arif, Z. U., Ahmed, W. & Arshad, H. Recent trends in recycling and reusing techniques of different plastic polymers and their composite materials. *Sustain. Mater. Techno*. **31**, 1–21 (2022).
32. Velasco-Parra, J. A., Ramon-Valencia, B. A. & Lopez-Arraiza, A. Effects of seawater immersion on a glass fibre reinforced bioepoxy mechanical properties and its application in the ship hull finite-element analysis. *Proc. Inst. Mech. Eng. Part. L*. **236**, 147–154 (2022).
33. Gomez-Campos, A., Vialle, C., Rouilly, A., Sablayrolles, C. & Hamelin, L. Flax fiber for technical textile: A life cycle inventory. *J. Clean. Prod.* **281**, 1–15 (2021).
34. Seile, A., Spurina, E. & Sinka, M. Reducing global warming potential impact of Bio-Based composites based of LCA. *Fibers* **10**, 1–19 (2022).
35. Das, S. C., La Rosa, A. D. & Grammatikos, S. A. *Chapter 19 - life cycle assessment of plant fibers and their composites in plant fibers, their composites, and applications.* 457–484 (Woodhead Publishing, 2022).
36. Gonzalez, V., Lou, X. & Chi, T. Evaluating environmental impact of natural and synthetic fibers: a life cycle assessment approach. *Sustainability* **15**, 1–16 (2023).
37. Ead, A. S., Appel, R., Alex, N., Ayranci, C. & Carey, J. P. Life cycle analysis for green composites: A review of literature including considerations for local and global agricultural use. *J. Eng. Fiber Fabr*. **16**, 1–20 (2021).
38. Perez-Martinez, B. B. et al. Recycling of plastic-rich streams from waste electrical and electronic equipment (WEEE) sorting plants: an in-depth study of pyrolysis potential through product characterization and life cycle assessment (LCA). *Energy Convers. Manag.* **329**, 1–14 (2025).
39. Shuaib, N., Aizat, M. & Paul, T. Energy demand in mechanical recycling of glass fibre reinforced thermoset plastic composites. *J. Clean. Prod.* **120**, 198–206 (2016).
40. Urain, I., Eguren, J. A., Mendoza, J., Manuel, F. & Justel, D. Analyzing the scope and effectiveness of business-level circularity indicators. *J. Ind. Ecol.* **28** (6), 1871–1882 (2024).
41. UNIFE life-cycle assessment topical group (LCA TG). Railway applications: recyclability and recoverability calculation method for rolling stock. *UNIFE* (2025).
42. Jani, H. K., Kachhwaha, S. S., Nagababu, G. & Das, A. A brief review on recycling and reuse of wind turbine blade materials. *Mater. Today Proc.* **62** (13), 7124–7130 (2022).

Author contributions

The individual contributions to the development of this research article were as follows: A.L-A., M.I., conceived and designed the study; L.E. D.B-F., performed the research; D.J., M.I. analyzed the data; A.L-A wrote the manuscript. All authors reviewed the manuscript.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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