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Eco-Efficiency Performance for Multi-Objective Optimal Design of Carbon/Glass/Flax Fibre-Reinforced Hybrid Composites

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Abstract: An eco-efficiency optimisation study on unidirectional carbon/glass fibre-reinforced hybrid composites with natural fibre (i.e., flax) and without flax is presented in this paper. The mechanical performance was assessed by determining the flexural properties obtained via finite element analysis (FEA)-based simulation. Given the required flexural strength, optimal candidate designs were found using a set of design rules and regression analysis, with minimising the cost and weight being the objectives. An eco-efficiency framework was applied to determine the eco-efficient hybrid composites. Life cycle assessment was an indispensable component of the framework as it helped determine the life cycle environmental impacts and costs of the hybrid composite materials. The environmental impacts and cost values were converted to the eco-efficiency portfolios of these composites for both comparison and selection purposes. The hybrid composites using bio-based flax fibre have been found to be eco-efficient in most of the cases due to the avoidance of energy-intensive and expensive reinforcing materials. The environmental impacts of the hybrid composites using flaxes are 12 to 13% less than the ones using no flaxes and the former are 7 to 13% cheaper than the latter, making the flax-based hybrid composites eco-efficient.

Keywords: hybrid composites; carbon; glass; flax; flexural; eco-efficiency; life cycle analysis (LCA); finite element analysis (FEA)

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1. Introduction

Fibre-reinforced hybrid composites are created by reinforcing a matrix with two or more types of fibres. Previous research [1] has demonstrated that, for layered composite materials, the flexural strength can be enhanced through the hybridisation of carbon and glass fibres. Additionally, the inclusion of higher strain-to-failure glass fibre plies has been found to improve the strain-to-failure [2]. The observed hybrid effect holds the potential to be a valuable strategy for achieving a well-balanced composite material that optimises both the cost and weight.

Natural fibre-reinforced composites have garnered significant research interest due to their numerous advantages. These composites, characterised by their lightweight nature, cost-effectiveness, abundant raw materials, and excellent recyclability, offer a compelling solution for various applications. The exploration of natural fibre composites presents a promising avenue for addressing the recycling of agricultural residues, thus contributing to sustainable waste management practices. Research investigations have demonstrated the potential of natural fibre composites to replace conventional glass fibre composites in a variety of applications [3].

Two crucial design objectives are the minimisation of the weight and cost. These objectives often conflict with each other, necessitating a trade-off. The optimisation challenge aimed at minimising both the cost and weight of composites is referred to as a multi-objective optimisation problem.

In our previous research, we employed NSGA-II (Non-Dominated Sorting Genetic Algorithm II) to minimise the cost and weight of both unidirectional [4,5] and multidirectional [6] carbon/glass fibre-reinforced hybrid composites. These studies involved determining the flexural properties of composites through an analytical approach based on the principles of cross-laminated timber (CLT). However, the application of NSGA-II coupled with finite element analysis (FEA) rendered the optimisation infeasible due to excessive time consumption. To address this, a previous study introduced a design rule-based optimisation approach for carbon/glass fibre-reinforced hybrid composites [5]. This approach involved developing a set of design rules based on theoretical and numerical analyses. By employing these design rules, various stacking configurations were generated. The connection between the flexural strength and fibre volume fractions was established using FEA and regression analysis. To meet the specified minimum flexural strength, an optimisation process was carried out for the hybrid composite under flexural loading, with the primary goals being the reduction in both the cost and weight.

While carbon and glass fibre-reinforced hybrid composites have excellent mechanical properties, their environmental impact is a concern. On the other hand, flax fibre composites are more sustainable but face challenges in terms of supply and performance. Hybrid composites that combine these materials aim to balance performance and sustainability. A study has found that a carbon/flax hybrid system is 15% cheaper, 7% lighter, and displays 58% greater vibration damping qualities over a full carbon fibre composite [7]. Flax has a higher fibre content, which causes less pollution in the synthetic polymer matrix, and is significantly lighter, which may reduce the amount of driving fuel required for transporting the fibres and their applied components [8].

Life cycle analysis (LCA) is a tool used to assess the environmental impacts associated with all stages of a product's life, from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling [9]. This approach, often referred to as a "cradle-to-grave" analysis, helps to provide a comprehensive view of the environmental aspects of the product and its potential impacts [10].

In the context of composites, LCA is particularly relevant. Composites, especially green composites made of natural materials, are claimed to have lower negative environmental effects due to their sustainability and easier recyclability. However, to substantiate these claims, a thorough LCA is needed [11].

Flax fibre is suitable for a particularly low-density reinforcement as it has a high resin uptake that makes the laminates considerably thicker, for a given weight of reinforcement, than would be for commonly used carbon or glass fibre. The environmental aspect of the use of flax is that it is a natural plant fibre that uses production methods with low environmental impacts, and it requires no irrigation [11]. The LCA of Dissanayake [12] found that flaxes are better sustainable alternatives to glass fibres for the reinforcement of polymer matrix composites. However, this may not always be the case as the LCA conducted by Deng and Tien [13] found that flax polypropylene floor mats (mat-PP) have 0.8–2 times higher environmental impact values than the glass mat-PP in most environmental impact categories over the production and end-of-life (EoL) phases due to the use of less-efficient technologies in flax cultivation and fibre processing in China. Similarly, Jacobsson [14] found that the production and use of fertilisers contribute to 70–90% of the total life cycle environmental impacts of flax fibre production in Sweden. It appears that the environmental impacts of flax fibre vary across regions.

It is shown from the literature that no research has been conducted for the optimisation and LCA for the carbon/glass/flax fibre-reinforced hybrid composite. The novelty of this study is to explore the sustainability benefits of the use of carbon/glass/flax fibre composites, which are structurally sound and meet the standard or technically feasible specifications, but their environmental and economic implications warrant further investigation to come up with a decisive strategy. In addition, the methodology or the framework that is considered in this paper is applied for the first time to this composite material-based research to determine the eco-efficient options. Lastly, to the best of our knowledge, this is probably the first study on the carbon/glass/flax hybrid composite, which aims at combining the advantages of carbon/glass and carbon/flax hybrid composites.

Thus, this study aims at filling this technical gap. It should be noted that a region-specific study on the LCA of the use of flax fibre in hybrid composites is important for Australia as no such study has been carried out in Australia. Also, it is equally important to assess the economic viability of the use of flax in hybrid composites to find out the mix with the lower environmental and economic impacts. An eco-efficiency framework has been utilised as it helps integrate the environmental cost results resulting from the LCA analysis to determine the eco-efficiency performance of the hybrid composites. This study is the first of its kind in Australia, as it applies the eco-efficiency framework under Australia's conditions to assess the eco-efficiency performance of hybrid composites reinforced by flax as opposed to carbon and glass fibres.

2. Materials and Methods

A flowchart for the methodology in this study is shown in Figure 1. The flexural properties for the potential layups obtained using the design rules are modelled by FEA. Regression models are then developed based on the FEA data. Given the required minimum flexural strength, the optimal candidates are obtained using the regression-based models. Life cycle assessment and eco-efficiency portfolio analysis are then performed for the optimal candidates.

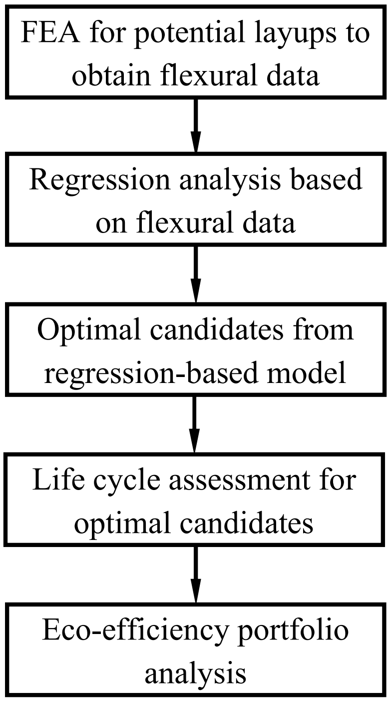


Figure 1. Flowchart for the methodology.

2.1. Material Properties

Typical values of the properties of the fibres and epoxy resin are given in Table 1 [4,15].

Table 1. Material properties of carbon fibre, E glass fibre, flax fibre, and epoxy resin.

Material	Tensile Modulus (GPa)	Tensile Strength (MPa)	Density (g/cm^3)	Normalised Density	Normalised Cost
High-strength carbon fibre	230 [4]	4900 [4]	1.8 [4]	1.6514	5.7710
E glass fibre	72 [4]	3450 [4]	2.58 [4]	2.3670	0.4122
Flax fibre	59 [13]	345 [13]	1.5 [13]	1.3761	0.1782
Epoxy resin	3.1 [4]	69.6 [4]	1.09 [4]	1	1

The weight of a composite material can be characterised by its density. The density of the hybrid composite reinforced by carbon, glass, and flax fibres, ρ_c, can be derived based on the rule of mixtures (RoM) as follows:

$$\rho_c = \left[\rho_{fc}V_{fc} + \rho_m\left(1 - V_{fc}\right)\right]f_c + \left[\rho_{fg}V_{fg} + \rho_m\left(1 - V_{fg}\right)\right]f_g + \left[\rho_{ff}V_{ff} + \rho_m\left(1 - V_{ff}\right)\right]f_f \tag{1}$$

where ρ_{fc}, ρ_{fg}, ρ_{ff}, and ρ_m are the densities of the carbon fibre, glass fibre, flax fibre, and the matrix, respectively; V_{fc}, V_{fg}, and V_{ff} are the fibre volume fractions of the carbon/epoxy, glass/epoxy, and flax/epoxy plies, respectively; f_c, f_g, and f_f are the volume fractions of the carbon/epoxy, glass/epoxy, and flax/epoxy plies, respectively.

The material cost of the hybrid composite, C_c, is given by

$$C_c = \left[C_{fc}V_{fc} + C_m\left(1 - V_{fc}\right)\right]f_c + \left[C_{fg}V_{fg} + C_m\left(1 - V_{fg}\right)\right]f_g + \left[C_{ff}V_{ff} + C_m\left(1 - V_{ff}\right)\right]f_f \tag{2}$$

where C_{fc}, C_{fg}, C_{ff}, and C_m are the costs of the carbon fibre, glass fibre, flax fibre, and the matrix, respectively.

2.2. Design Rule-Based Optimisation

In this study, the flexural strength of hybrid composites was obtained by an FEA-based model, and the details are given in a previous study [5]. FEA has been widely used for modelling composite materials because it can handle complex material properties, geometry, and boundary conditions [16–18]. A brief description of the FEA-based model is given here. A three-point bend test in accordance with ASTM D7264 [19] is simulated via FEA using Ansys Workbench to obtain the flexural properties. The hybrid composite specimen (100 × 10 × 2 mm^3) consisting of eight 0.25 mm plies is modelled as a shell with the layup being defined using Ansys ACP. Two supports, modelled as cylindrical solids, support the composite specimen at a span of L. The loading nose, also modelled as a cylindrical solid, applies a prescribed displacement of 7 mm at the mid-span. A span-to-thickness ratio of 32 is chosen, ensuring a standard testing condition. A linear static analysis is performed to simulate the first ply failure. The flexural properties are calculated using the FEA results. This modelling approach has been validated against experimental data in a previous study [20]. It has been proven that the flexural properties of hybrid composites reinforced by two types of fibres can be simulated with confidence.

For the carbon/glass fibre-reinforced hybrid composite, the potential optimal layups for the carbon/glass fibre-reinforced hybrid composite derived by the design rules are given in Table 2 [5]. For all layups, from left to right corresponds to from compression (ply 8) to tension (ply 1).

Table 2. Potential layups for carbon/glass hybrid composite [5].

Number of Glass/Epoxy Plies	Layup
0	$[0]_{8C}$
1	$[0_G/0_{7C}]$
2	$[0_{2G}/0_{6C}]$ $[0_{4C}/0_{2G}/0_{2C}]$
3	$[0_{2G}/0_{2C}/0_G/0_{3C}]$ $[0_G/0_{3C}/0_{2G}/0_{2C}]$ $[0_{3C}/0_{3G}/0_{2C}]$
4	$[0_{2G}/0_{2C}]_2$
5	$[0_{2G}/0_{2C}/0_{3G}/0_C]$
6	$[0_{2G}/0_C/0_{4G}/0_C]$ $[0_{3G}/0_C]_2$
7	$[0_{7G}/0_C]$
8	$[0]_{8G}$

For the carbon/glass/flax fibre-reinforced hybrid composite, carbon or glass fibre plies should be employed to reinforce the tensile and compressive sides of the hybrid composite under flexural loading, and flax fibre plies should be placed around the neutral plane. The potential layups are shown in Table 3.

Table 3. Potential layups for carbon/glass/flax hybrid composite.

Number of Flax/Epoxy Plies	Number of Glass/Epoxy Plies	Layup
2	0	$[0_{3C}/0_{3F}/0_{2C}]$
3	1	$[0_{G}/0_{2C}/0_{3F}/0_{2C}]$
3	2	$[0_{2G}/0_{C}/0_{3F}/0_{2C}]$
4	0	$[0_{2C}/0_{2F}]_{S}$
4	2	$[0_{2G}/0_{4F}/0_{2C}]$

Table 1 reveals that flax fibre exhibits a lower density and cost in comparison to glass fibre. To minimise both the density and cost, it is advisable to maximise the utilisation of flax fibre in the hybrid composite. Thus, the fibre volume fraction of the flax/epoxy plies is fixed at 0.6. For a given layup, the fibre volume fractions of both the carbon/epoxy and glass/epoxy plies are varied between 0.3 and 0.6, and the flexural strengths are obtained. A response surface for the flexural strength is then constructed. As an example, the response surface for layup $[0_{G}/0_{2C}/0_{3F}/0_{2C}]$ is shown in Figure 2. In Figure 2, the contour lines represent the flexural strengths in MPa.

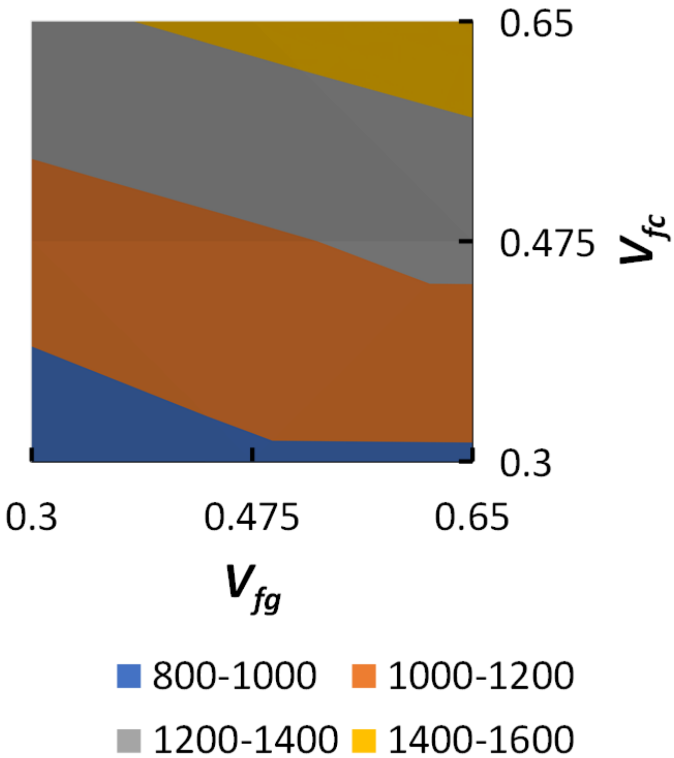


Figure 2. Flexural strength vs. V_{fg} and V_{fc} for layup $[0_{G}/0_{2C}/0_{3F}/0_{2C}]$.

To quantitatively evaluate the flexural strength, a regression model is developed, given by

$$S_F = c_0 + c_{c1}V_{fc} + c_{c2}V_{fc}^2 + c_{g1}V_{fg} + c_{g2}V_{fg}^2 + c_{cg}V_{fc}V_{fg} \quad (3)$$

where c_0, c_{c1}, c_{c2}, c_{g1}, c_{g2}, and c_{cg} are constants to be determined by Least Squares Estimation (LSE). When establishing these constants, constraints are applied to ensure that the flexural strengths obtained from the regression formula are either less than or equal to those derived from the FEA. The regression constants for layup $[0_G/0_{2C}/0_{3F}/0_{2C}]$ are given in Table 4 and the flexural strengths from the FEA and regression are given in Table 5.

Table 4. Regression coefficients for layup $[0_G/0_{2C}/0_{3F}/0_{2C}]$.

Regression Coefficient	Value
c_0	459.137
c_{c1}	609.107
c_{c2}	498.108
c_{g1}	899.859
c_{g2}	715.734
c_{cg}	−530.574

Table 5. Flexural strengths from FEA and regression for layup $[0_G/0_{2C}/0_{3F}/0_{2C}]$.

V_{fc}	V_{fg}	Flexural Strength from FEA (MPa)	Flexural Strength from Regression (MPa)
0.3	0.3	888.95	888.95
0.3	0.45	973.60	944.47
0.3	0.6	976.12	976.12
0.45	0.3	1101.33	1101.33
0.45	0.45	1177.10	1177.10
0.45	0.6	1254.13	1228.99
0.6	0.3	1364.71	1345.92
0.6	0.45	1441.93	1441.93
0.6	0.6	1514.07	1514.07

Given the required flexural strength, the fibre volume fractions of the carbon/epoxy and glass/epoxy plies can be obtained by solving the equation $c_{c2}V_{fc}^2 + \left(c_{c1} + c_{cg}V_{fg}\right)V_{fc} - \left(S_F - c_0 - c_{g1}V_{fg} - c_{g2}V_{fg}^2\right) = 0$. If V_{fg} is given, V_{fc} is given by

$$V_{fc} = \frac{-\left(c_{c1} + c_{cg}V_{fg}\right) + \sqrt{\left(c_{c1} + c_{cg}V_{fg}\right)^2 + 4c_{c2}\left(S_F - c_0 - c_{g1}V_{fg} - c_{g2}V_{fg}^2\right)}}{2c_{c2}} \quad (4)$$

If the hybrid composite does not contain glass fibre, the regression model for the flexural strength is given by $S_F = c_0 + c_{c1}V_{fc} + c_{c2}V_{fc}^2$. Solving the equation, the fibre volume fraction of the carbon/epoxy plies for any given flexural strength is given by

$$V_{fc} = \frac{-c_{c1} + \sqrt{c_{c1}^2 + 4c_{c2}(S_F - c_0)}}{2c_{c2}} \quad (5)$$

In this study, two specific minimum flexural strengths, namely 1000 MPa and 1300 MPa, are selected. To meet the specified minimum flexural strength, various potential layups presented in Table 3 are explored by adjusting the fibre volume fractions. The associated costs and weights are documented. Following a comprehensive exploration of all layups, a plot is generated, depicting the relationship between the weight and cost. The lower boundary of this plot establishes the Pareto front. It is important to note that a single layup may have multiple combinations of fibre volume fractions that satisfy the required flexural strength.

2.3. Life Cycle Assessment

LCA evaluates the environmental and economic viability of the use of flax as a reinforcement material in the production of hybrid composites. In accordance with the ISO 14040 [21], the LCA was performed in four stages, i.e., goal and scope, inventory analysis, impact assessment, and interpretation. The goal is to compare the degree of eco-efficiency of hybrid composite materials with flax and without flax. The scope involves the production and sourcing of composites and the energy consumed during the conversion of multiple materials to hybrid composites. The functional unit used in the LCA is to compare the environmental and economic performance of hybrid composites offering the same flexural strength. The same functional unit was also considered for the life cycle cost (LCC), which is the cost per flexural strength (i.e., AUD/MPa). Both LCA and LCC have been conducted for two flexural strengths: 1000 MPa and 1300 MPa.

LCI was used to calculate the relevant environmental impacts during the life cycle stages of hybrid composites, including raw materials extraction, energy consumption, transport between consecutive stages, and manufacturing of hybrid composites. The importance of this stage is to define the exact inputs going into the creation of the item at a specific time and place. The processes and transport methods for identical items created in different locations can vary the overall impacts. This study considers the emissions from the transportation of materials for making hybrid composites. The unit of transportation is in tkm (tonne kilometers travelled), as the emission factor for transportation has this unit. Tables 6 and 7 show the LCIs of hybrid composites with flexural strengths of 1000 MPa and 1300 MPa, respectively.

The LCI data of Tables 6 and 7 were entered into the Simapro 9.4 LCA software to determine the total environmental impacts resulting from the production of one cubic meter of hybrid composites. The environmental impacts estimated are the direct consequences of the release of pollutants into the environment or their equivalent.

Table 6. LCI of hybrid composite materials offering a flexural strength of 1000 MPa.

Specimens	Materials					Mfg	tkm		Cost
	Carbon	Glass	Flax	Epoxy	kg/L	MJ	Sea	Road	\$/litre
with flax									
$[0_{3C}/0_{3F}/02_{C}]$	0.33	0.00	0.31	0.57	1.22	26.63	4.92	0.024	46.6
$[0_{2C}/0_{2F}]_{S}$	0.31	0.00	0.41	0.51	1.24	27.06	5.00	0.025	43.3
$[0_{G}/0_{2C}/0_{3F}/0_{2C}]$	0.29	0.12	0.31	0.55	1.27	27.75	5.13	0.025	42.4
$[0_{G}/0_{2C}/0_{3F}/0_{2C}]$	0.26	0.18	0.31	0.54	1.29	28.25	5.22	0.026	39.9
$[0_{G}/0_{2C}/0_{3F}/0_{2C}]$	0.23	0.24	0.31	0.54	1.31	28.74	5.31	0.026	37.2
$[0_{G}/0_{2C}/0_{3F}/0_{2C}]$	0.20	0.30	0.31	0.53	1.33	29.20	5.40	0.027	34.4
$[0_{G}/0_{2C}/0_{3F}/0_{2C}]$	0.19	0.36	0.31	0.51	1.36	29.85	5.51	0.027	33.1
$[0_{2G}/0_{4F}/0_{2C}]$	0.13	0.36	0.41	0.47	1.37	29.95	5.53	0.027	27.0
without flax									
$[0]_{8C}$	0.54	0.00	0.00	0.67	1.21	26.61	4.92	0.024	67.5
$[0_{G}/0_{7C}]$	0.43	0.14	0.00	0.68	1.25	27.48	5.08	0.025	58.1
$[0_{2G}/0_{6C}]$	0.37	0.25	0.00	0.67	1.29	28.22	5.21	0.026	52.7
$[0_{2G}/0_{2C}/0_{G}/0_{3C}]$	0.34	0.34	0.00	0.65	1.33	29.11	5.38	0.027	49.8
$[0_{2G}/0_{2C}]_{2}$	0.29	0.41	0.00	0.65	1.35	29.56	5.46	0.027	45.4
$[0_{2G}/0_{2C}/0_{3G}/0_{C}]$	0.24	0.49	0.00	0.65	1.38	30.16	5.57	0.028	41.3
$[0_{2G}/0_{C}/0_{4G}/0_{C}]$	0.16	0.70	0.00	0.61	1.47	32.12	5.93	0.029	33.5
$[0_{2G}/0_{C}/0_{4G}/0_{C}]$	0.12	0.85	0.00	0.57	1.54	33.75	6.23	0.031	30.0
$[0_{7G}/0_{C}]$	0.12	0.95	0.00	0.52	1.60	35.00	6.47	0.032	29.2
$[0_{7G}/0_{C}]$	0.06	1.13	0.00	0.49	1.68	36.71	6.78	0.034	23.5
$[0]_{8G}$	0.00	1.42	0.00	0.40	1.82	39.86	7.36	0.036	17.0

Table 7. LCI of hybrid composite materials offering a flexural strength of 1300 MPa.

Specimens	Materials Carbon	Glass	Flax	Epoxy	sp wt	Mfg MJ	tkm Sea	Road	Cost $/litre
with flax									
$[0_{3C}/0_{3F}/0_{2C}]$	0.47	0.00	0.31	0.49	1.27	27.8	5.14	0.025	57.2
$[0_{2C}/0_{2F}]_S$	0.43	0.00	0.41	0.44	1.28	28.1	5.19	0.026	52.4
$[0_G/0_{2C}/0_{3F}/0_{2C}]$	0.42	0.15	0.31	0.46	1.34	29.3	5.40	0.027	52.2
$[0_G/0_{2C}/0_{3F}/0_{2C}]$	0.40	0.18	0.31	0.46	1.35	29.5	5.45	0.027	50.8
$[0_G/0_{2C}/0_{3F}/0_{2C}]$	0.34	0.30	0.31	0.44	1.39	30.5	5.63	0.028	45.4
$[0_G/0_{2C}/0_{3F}/0_{2C}]$	0.31	0.33	0.31	0.45	1.40	30.6	5.65	0.028	42.9
$[0_G/0_{2C}/0_{3F}/0_{2C}]$	0.29	0.36	0.31	0.45	1.41	30.8	5.69	0.028	41.3
without flax									
$[0]_{8C}$	0.77	0.00	0.00	0.54	1.30	28.5	5.27	84.3	84.3
$[0_{4C}/0_{2G}/0_{2C}]$	0.58	0.18	0.00	0.58	1.33	29.1	5.38	0.027	68.6
$[0_{3C}/0_{3G}/0_{2C}]$	0.49	0.27	0.00	0.59	1.35	29.5	5.44	0.027	61.2
$[0_{2G}/0_{6C}]$	0.46	0.35	0.00	0.57	1.38	30.3	5.60	0.028	58.6
$[0_{2C}/0_{2G}]$s	0.43	0.40	0.00	0.57	1.40	30.6	5.66	0.028	56.1
$[0_{2G}/0_{2C}/0_{3G}/0_C]$	0.37	0.47	0.00	0.58	1.42	31.1	5.75	0.028	51.2
$[0_{2G}/0_{2C}/0_{3G}/0_C]$	0.33	0.62	0.00	0.54	1.49	32.6	6.02	0.030	47.0
$[0_{2G}/0_C/0_{4G}/0_C]$	0.25	0.79	0.00	0.52	1.55	34.0	6.29	0.031	39.8
$[0_{2G}/0_C/0_{4G}/0_C]$	0.17	1.07	0.00	0.45	1.68	36.8	6.80	0.034	32.1

Following Bengtsson and Howard [22] and Renouf et al. [23], fourteen environmental impacts (Table 8), specific to Australian conditions and relevant to hybrid composites, were calculated. Each of these environmental impacts is associated with the emission of gases specific to environmental impacts. The environmental impacts of each hybrid composite were calculated by multiplying the input values in the LCI by the corresponding emission factors. The environmental impact values are then normalised and weighted in converting them to a common unit, known as "eco-point", using Equations (6) and (7) [24,25].

$$N_{HCMe} = \frac{EI_{HCM}}{GI_{HCM}} \tag{6}$$

where the values for each environmental impact (EI) are divided by the corresponding gross domestic environmental impact (GI) to determine the normalised environmental impact value of each type of hybrid composite, N_{HCMe} [24,25].

$$E_{HCMe} = \sum N_{HCMe} \times W_{HCMi} \tag{7}$$

where the normalised values for individual environmental impacts were multiplied by the corresponding weights (W_{HCMi}) for conversion to a common unit. The sum of all the weighted normalised values is the normalised environmental impact as expressed as E_{HCMe}.

The environmental impact values are in per m^3, which are converted to the values per MPa equivalent by using the corresponding flexural strength values of the hybrid composites.

Life cycle costs of hybrid composites offering 1000 MPa and 1300 MPa were calculated using Equation (8) [24,25].

$$N_{HCMc} = \frac{CS_{HCM}}{GDP}. \tag{8}$$

Both environmental and economic data were normalised to produce the eco-efficiency portfolio. The steps that were followed to calculate the eco-efficiency portfolios are discussed below. Firstly, the normalised economic cost (Nc) is calculated from the hybrid composite cost (CS), divided by the GDP per inhabitant or per capita.

Table 8. Impact assessment methods and normalisation factors (Bengtsson and Howard, 2010 [22]).

Environmental Impacts	Gross Domestic Environmental Impact	Weighting
Global warming potential	28,690 kg CO_2 eq	19.50%
Eutrophication	19 kg PO_4^{3-} eq	2.90%
Water depletion	930 m^3 H_2O	6.20%
Land use and ecological diversity	26 Ha a	20.90%
Photochemical smog	75 kg NMVOC	2.80%
Human toxicity	3216 kg 1,4-DB eq	2.70%
Terrestrial ecotoxicity	88 kg 1,4-DB eq	10.30%
Freshwater ecotoxicity	172 kg 1,4-DB eq	6.90%
Marine ecotoxicity	12,117,106 kg 1,4-DB eq	7.70%
Ionising radiation	1306 kg U235 eq	1.90%
Ozone depletion	0.002 kg CFC-11 eq	3.90%
Abiotic depletion	300 kg Sb eq	8.20%
Acidification	123 kg SO_2 eq	3.10%
Respiratory inorganics	45 kg $PM_{2.5}$ eq	3.00%

2.4. Eco-Efficiency Portfolio Analysis

This involves the calculation of eco-efficiency portfolios of the hybrid composite materials for conducting a comparative analysis.

The first step was to calculate the initial positions (*iPP*) for the eco-efficiency portfolio, which is the ratio of the normalised cost and environmental impact for each type of hybrid composite material, as compared to the average normalised cost (i.e., N_{HCMcAV}) and environmental impact (i.e., E_{HCMeAV}) (Equations (9) and (10)).

$$iPP_{HCM,\,e} = \frac{E_{e\,HCMe}}{E_{HCMe\,AV}}, \tag{9}$$

$$iPP_{HCMc} = \frac{N_{c\,HCM}}{N_{HCMc\,AV}}. \tag{10}$$

The environmental to cost relevance factor R was determined to capture the changes in the portfolio position of each hybrid composite due to the changes in the cost or environmental impact of other materials. R is expressed using Equation (11) [24,25].

$$R = \frac{E_{HCMe\,AV}}{N_{HCMc\,AV}}. \tag{11}$$

The final portfolio positions of the hybrid composite were calculated by incorporating the environmental to cost relevance factor R into Equations (12) and (13) [20,21].

$$PP_{HCM,\,e} = \frac{iPP_{HCMAV,\,e} + (iPP_{HCM,\,e} - iPP_{HCMeAV,}\,) * \sqrt{R}}{iPP_{HCMe,\,AV,}}, \tag{12}$$

$$PP_{HCM\ c} = \frac{iPP_{HCMcAV,} + (iPP_{HCMc} - iPP_{HCMcAV,})/\sqrt{R}}{iPP_{HCMeAV}} \tag{13}$$

An eco-efficiency portfolio provided a visual representation for comparing the eco-efficiency performance of different hybrid composites in terms of the final portfolio positions. The hybrid composites with a low eco-efficiency have higher environmental impacts relative to the costs or vice versa; they are positioned below the diagonal line (Figure 3). Any option above the diagonal line is considered to be eco-efficient, representing a ratio of lower environmental impacts relative to the economic costs.

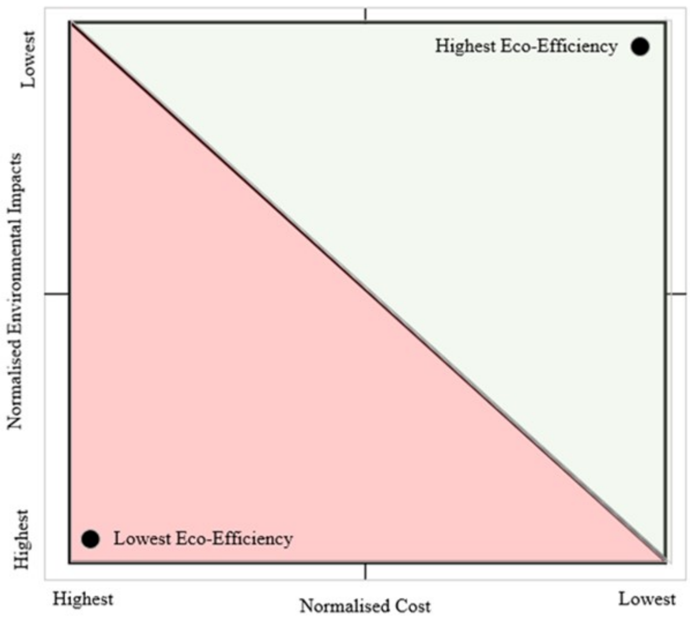


Figure 3. Eco-efficiency framework [26].

3. Results and Discussion

For comparison, the selected candidates for the carbon/glass/flax fibre-reinforced hybrid composite from the optimisation are shown in Tables 9 and 10. The selected candidates were given codes for facilitating the analysis and interpretation of results.

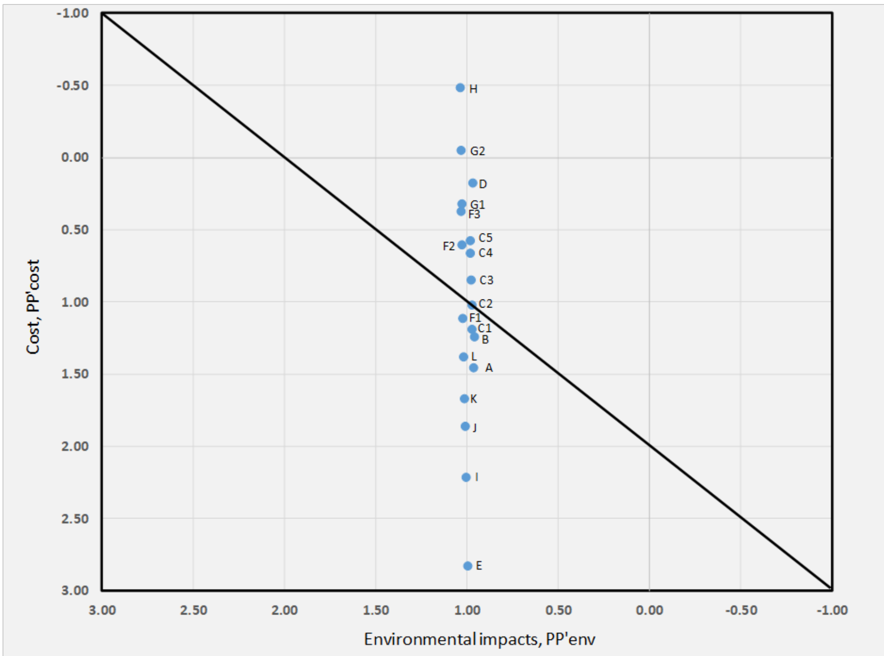
Table 9. Optimal designs of carbon/glass/flax fibre-reinforced hybrid composite with minimum flexural strength of 1000 MPa.

Layup (ply 8–ply 1)	Code	Layup (ply 8–ply 1)	Code
$[0_{4C}/0_{2F}/0_{2C}]$	A	$[0]_{8C}$	E
$[0_{2C}/0_{2F}]_S$	B	$[0_G/0_{7C}]$	I
$[0_G/0_{2C}/0_{3F}/0_{2C}]$	C1	$[0_{2G}/0_{6C}]$	J
$[0_G/0_{2C}/0_{3F}/0_{2C}]$	C2	$[0_{2G}/0_{2C}/0_G/0_{3C}]$	K
$[0_{2G}/0_C/0_{3F}/0_{2C}]$	C3	$[0_{2G}/0_{2C}]_2$	L
$[0_{2G}/0_C/0_{3F}/0_{2C}]$	C4	$[0_{2G}/0_{2C}/0_{3G}/0_C]$	F1
$[0_{2G}/0_C/0_{3F}/0_{2C}]$	C5	$[0_{2G}/0_C/0_{4G}/0_C]$	F2
$[0_{2G}/0_{4F}/0_{2C}]$	D	$[0_{2G}/0_C/0_{4G}/0_C]$	F3
		$[0_{7G}/0_C]$	G1
		$[0_{7G}/0_C]$	G2
		$[0]_{8G}$	H

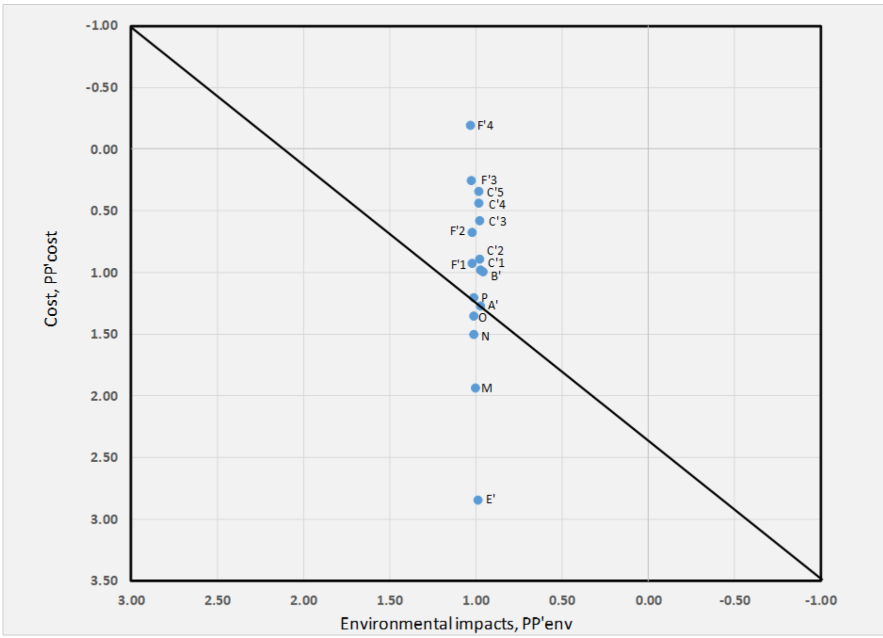
Table 10. Optimal designs of carbon/glass/flax fibre-reinforced hybrid composite with minimum flexural strength of 1300 MPa.

Layup (ply 8–ply 1)	Code	Layup (ply 8–ply 1)	Code
$[0_{4C}/0_{2F}/0_{2C}]$	A′	$[0]_{8C}$	E′
$[0_{2C}/0_{2F}]_S$	B′	$[0_{4C}/0_{2G}/0_{2C}]$	M
$[0_G/0_{2C}/0_{3F}/0_{2C}]$	C′1	$[0_{3C}/0_{3G}/0_{2C}]$	N
$[0_G/0_{2C}/0_{3F}/0_{2C}]$	C′2	$[0_{2G}/0_{6C}]$	O
$[0_{2G}/0_C/0_{3F}/0_{2C}]$	C′3	$[0_{2C}/0_{2G}]_s$	P
$[0_{2G}/0_C/0_{3F}/0_{2C}]$	C′4	$[0_{2G}/0_{2C}/0_{3G}/0_C]$	F′1
$[0_{2G}/0_C/0_{3F}/0_{2C}]$	C′5	$[0_{2G}/0_{2C}/0_{3G}/0_C]$	F′2
		$[0_{2G}/0_C/0_{4G}/0_C]$	F′3
		$[0_{2G}/0_C/0_{4G}/0_C]$	F′4

Figure 4 shows that the increase in the use of flax in the hybrid composite materials of 1000 MPa can help achieve eco-efficiency by reducing the use of expensive and energy-intensive carbon/glass fibre. The specimens without flax are not eco-efficient as they are below the diagonal lines. Most of the specimens using flax are eco-efficient as they are above the diagonal line. Only two specimens that use flax (i.e., A and B) were not found to be eco-efficient due to having a lesser amount of flax. In the case of hybrid composites of 1300 MPa, all composites using flax are eco-efficient as the use of a higher amount of energy- and carbon-intensive carbon/glass fibre can be avoided at a higher flexural strength.



(**a**)



(**b**)

Figure 4. Eco-efficiency portfolios of carbon/glass/flax fibre -_reinforced hybrid composite with minimum flexural strength of 1000 MPa (**a**) and 1300 (**b**).

There are mainly two reasons why the hybrid composites using flax are eco-efficient. Firstly, the hybrid composites using flax are cheaper than those without flax. The average cost of hybrid composites with a flexural strength of 1000 MPa using flax is 7% cheaper than those without flax. For the hybrid composites with a flexural strength of 1300 MPa, the hybrid composites without flax have a 13% higher cost than those without flax, resulting from the higher cost of carbon and glass fibres (Tables 4 and 5). Secondly, the hybrid composites without flax have higher environmental impacts than those without flax (Table 11). The hybrid composites using no flaxes have 12% to 13% more environmental impacts than the ones with flaxes. The impacts that are mainly responsible for increasing the overall impact are global warming impacts (55%), photochemical smog (13%), and acidification (11%) (Figure 5). Figure 5 shows the breakdown of impacts based on the average values of the impacts for hybrid composites with a flexural strength of 1000 MPa. Other studies also found GWPs as the dominant impacts for both flax and glass/carbon fibre-reinforced hybrid composites [13,27].

Table 11. Environmental impacts of hybrid composites of 1000 and 1300 MPa flexural strengths.

1000 MPa		1300 MPa	
Hybrid Composite	**Environmental Impacts per Inhabitants**	**Hybrid Composite**	**Environmental Impacts per Inhabitants**
with flax			
A	0.14	A′	0.13
B	0.13	B′	0.13
C1	0.14	C′1	0.13
C2	0.14	C′2	0.13
C3	0.14	C′3	0.14
C4	0.14	C′4	0.14
C5	0.14	C′5	0.14
D	0.14		
without flax			
E	0.15	E′	0.14
F1	0.16	F′1	0.15
F2	0.16	F′2	0.15
F3	0.16	F′3	0.16
G1	0.16	F′4	0.16
G2	0.16	M	0.15
H	0.16	N	0.15
I	0.15	O	0.15
J	0.15	P	0.15
K	0.15		
L	0.16		

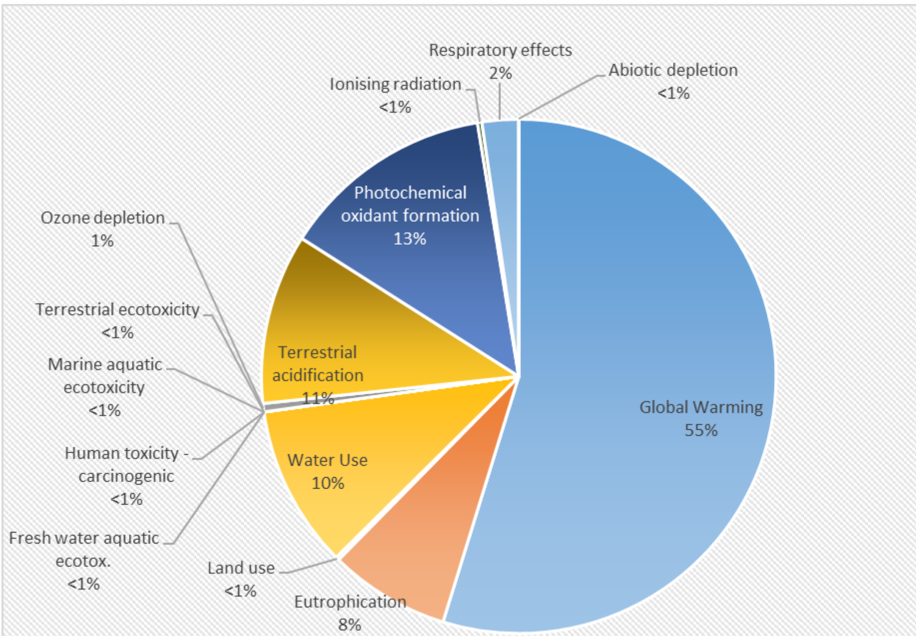


Figure 5. Eco-efficiency portfolios of carbon/glass/flax fibre-reinforced hybrid composites with minimum flexural strength of 1300 MPa.

The GWP or carbon footprint has been found to be the hotspot and the replacement of carbon/glass fibre with flax-reinforcing materials can reduce GWPs by 12.5%. This carbon footprint-saving potential of flax-reinforced hybrid composites has a significant bearing on achieving the net zero emissions target.

4. Conclusions

The breakthrough of the research in this study is that it could probably be the first study on the carbon/glass/flax hybrid composite, which aims at combining the advantages of carbon/glass and carbon/flax hybrid composites. Hybrid composite materials using flax as a reinforcement material have been found to have a better eco-efficiency performance than those using conventional carbon/glass-reinforcement materials for different flexural strengths under the Australian situation. This study proved that bio-based reinforcing materials could not only be a suitable substitute for conventional ones like carbon and glass fibres but they also have sustainability benefits, as confirmed by the eco-efficiency analysis that was applied for the first time in this material science research to the best of our knowledge. Both the economic and environmental benefits of the use of flax in hybrid composites increase with the increase in the flexural strength. Flax fibre-reinforced hybrid composites have been found to have a lower carbon footprint compared to ones using carbon/glass for reinforcing. This will assist manufacturers to achieve their net zero emissions targets.

Future research should consider durability and fatigue tests in order to determine the service life or longevity of these hybrid composite materials, as it is a determinant of resource efficiency in a resource-constrained world. In addition, social impacts can be carried out to assess the overall sustainability implications of the use of bio-based materials in hybrid composites as a replacement for non-renewable and carbon-intensive materials.

In addition to the above, a future study could consider the recyclability aspect of this hybrid composite material in an LCA study. It is a limitation of this study as it considered the "cradle to gate" approach or did not consider impacts during the use and end-of-life stages of the LCA for these hybrid materials. Usually, most (up to 90%) FRP waste will end up in a landfill as this is deemed to be the economically viable option. There are mechanical, thermal, and chemical recycling processes although the mechanical crushing of FRPs currently seems to be the only viable option for industrial applications [28]. However, the advantage of the use of flax fibre in this situation is that it is biodegradable, and thus improves the overall recyclability of the composite as it decomposes naturally over time, reducing the amount of non-degradable material (such as carbon and glass fibres) that would otherwise have remained in the environment [29].

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