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Are natural fiber composites environmentally superior to glass fiber reinforced composites?

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Abstract

Natural fibers are emerging as low cost, lightweight and apparently environmentally superior alternatives to glass fibers in composites. We review select comparative life cycle assessment studies of natural fiber and glass fiber composites, and identify key drivers of their relative environmental performance. Natural fiber composites are likely to be environmentally superior to glass fiber composites in most cases for the following reasons: (1) natural fiber production has lower environmental impacts compared to glass fiber production; (2) natural fiber composites have higher fiber content for equivalent performance, reducing more polluting base polymer content; (3) the light-weight natural fiber composites improve fuel efficiency and reduce emissions in the use phase of the component, especially in auto applications; and (4) end of life incineration of natural fibers results in recovered energy and carbon credits.

Keywords: Natural fibers; A. Glass fibers

1. Introduction

Since the 1990s, natural fiber composites are emerging as realistic alternatives to glass-reinforced composites in many applications. Natural fiber composites such as hemp fiber-epoxy, flax fiber-polypropylene (PP), and china reed fiber-PP are particularly attractive in automotive applications because of lower cost and lower density. Glass fibers used for composites have density of ~ 2.6 g/cm^3 and cost between \$1.30 and \$2.00/kg. In comparison, flax fibers have a density of ~ 1.5 g/cm^3 and cost between \$0.22 and \$1.10/kg [1]. While, natural fibers traditionally have been used to fill and reinforce thermosets, natural fiber reinforced thermoplastics, especially polypropylene composites, have attracted greater attention due to their added advantage of recyclability [2]. Natural fiber composites are also claimed to offer environmental advantages such as reduced dependence on non-renewable energy/material sources, lower pollutant emissions, lower greenhouse gas emissions, enhanced energy recovery, and end of life biodegradability of components. Since, such superior environmental performance is an important driver of increased future use of natural fiber composites, a thorough comprehensive analysis of the relative environmental impacts of natural fiber composites and conventional composites, covering the entire life cycle, is warranted. In this article, we review select life cycle assessment (LCA) studies comparing natural fiber composites and glass fiber composites. We identify the major drivers of the relative environmental performance of natural fiber composites, and draw conclusions about whether the specific findings of these studies can be generalized.

2. Life cycle assessment

Life cycle assessment is a technique for assessing the environmental aspects and potential impacts associated with a product, by

- compiling an inventory of relevant inputs and outputs of a product system;

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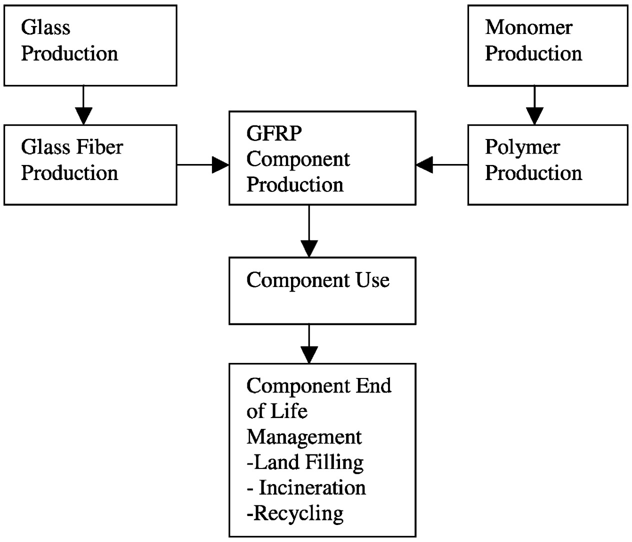

Fig. 1. Life cycle of a glass fiber reinforced composite component.

- evaluating the potential environmental impacts associated with those inputs and outputs;
- interpreting the results of the inventory analysis and impact assessment phases in relation to the objectives of the study.

LCA studies the environmental aspects and potential impacts throughout a product's life from raw material acquisition through production, use and end of life management options such as recycling, incineration and disposal [3]. LCA takes a comprehensive 'cradle to grave' or 'cradle to cradle' approach thus avoiding focus on only specific life cycle stages in product environmental performance evaluation. Recent series of ISO standards 14040 to 14043 provide detailed guidelines for conducting LCA.

Figs. 1 and 2 show simplified, generic life cycle stages of a component made from glass fiber reinforced composite material and a natural fiber composite material respectively.

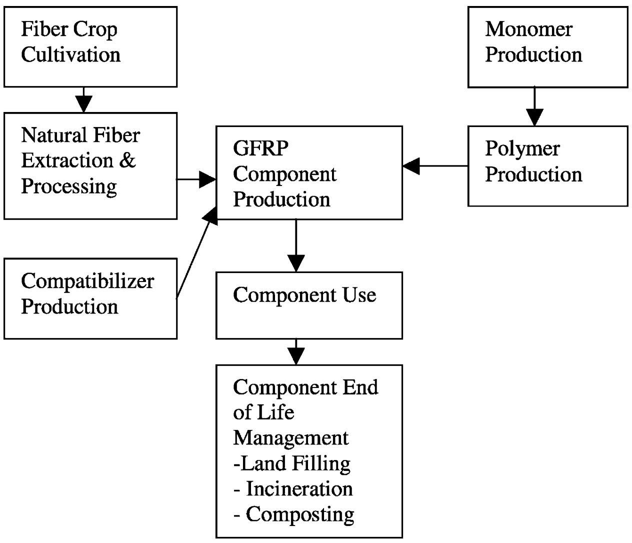

Fig. 2. Life cycle of a natural fiber reinforced composite component.

The details of specific material and energy flows, emissions and manufacturing processes vary depending on the specific application. However, material flows, energy use, emissions, and environmental impacts over all these stages need to be modeled, inventoried and analyzed for a comprehensive life cycle assessment.

3. Review of prior studies

A few studies have looked at comparative life cycle assessment of specific components made from glass fiber reinforced (GFR) composite materials and natural fiber reinforced (NFR) composite materials [4–7]. We summarize the methodology and findings from three studies available in English below.

3.1. Wotzel, Wirth and Flake, 1999 [7]

This study presents life cycle assessments of a side panel for Audi A3 car made from ABS co-polymer and an alternative design made from hemp fiber (66 vol%)-epoxy resin composite. The study models inputs, energy use and emissions up to the component manufacturing stage. The use phase and end of life management options such as energy recovery through incineration are not modeled, though the study discusses some implications of including the use phase. For the NFR component, cultivation of hemp, hemp fiber extraction and component manufacture stages are modeled. The data on life cycle emissions for the ABS and Epoxy resins are based on APME eco-profiles [8]. The cumulative energy use and select emissions from production of one component, reported in the study are summarized in Table 1.

The natural fiber component uses 45% less energy, and results in lower air emissions. However, water emissions of nitrates and phosphates, and nitrogen oxide (NO_x) emissions to air are higher as a result of fertilizer applications in hemp cultivation. Overall Eco-indicator point [9] scores are about 8% less for the hemp-fiber epoxy composite. The environmental impacts for the hemp-epoxy composite are

Table 1
Life cycle environmental impacts from production of one auto side panel [7]

Component material → environmental indicator ↓	ABS copolymer	Hemp-Epoxy
Total energy (MJ)	132	73
CO_2 emissions (kg)	4.97	4.19
Methane (g)	17.43	16.96
SO_2 (g)	17.54	10.70
NO_x (g)	14.14	18.64
CO (g)	4.44	2.14
Phosphate emissions to water (g)	0	0.09
Nitrate emissions to water (g)	0.08	12.05

dominated by the energy and emissions from epoxy production. Even though hemp fiber accounts for 66% of the volume of the component, it contributes only 5.3% of the cumulative energy demand.

3.2. Schmidt and Beyer 1998 [5]

Schmidt and Beyer conduct simplified LCAs of two designs of an insulation component for a Ford car. The reference component is made from ethylene propylene diene copolymer (EPDM), polypropylene (PP) and reinforced with glass fibers. The alternative component is also made from EPDM and PP but reinforced with hemp fibers (30 wt%). They consider the main inputs and emissions for glass fiber production, EPDM production, PP production, hemp fiber production, component moulding, use phase on the car, collection and disposal (assumed to be 50% land-filling and 50% incineration). The data for are mainly from public databases (glass fiber from PRe [10], PP and EPDM from APME [8], Fertilizer from BUWAL [11]) except for hemp fiber production, which are obtained from proprietary sources or estimated based on educated judgments. They present their final results only in the form of net benefits of switching to the hemp fiber component from GFR component. The hemp fiber component shows net benefits of 88.9 MJ in cumulative energy demand, 8.18 kg of CO2 emissions, 0.0564 kg of sulfur dioxide emissions, 0.002 kg of phosphate emissions and 0.018 kg of nitrate emissions in the basic scenario. They also conduct sensitivity analyses of the net benefits with respect to changes in assumptions regarding incineration, use phase distances driven, hemp transport distances, and cultivation energy, and find that the net benefit estimates are robust under the normal range of these parameters.

3.3. Corbiere-Nicollier et al. 2001 [4]

This study reports LCAs of transport pallets made from glass fiber reinforced PP, and china reed fiber reinforced PP, conducted by the researchers from the Federal Institute of Technology, Lausanne, Switzerland. The equivalent performance design of NFR pallet contains 53% china reed by weight, compared to GFR pallet which has 42% by weight of glass fiber. The system boundary for the LCA covers PP production, china reed cultivation, fiber extraction, compatibilizer production, intermediate transport, pallet production, pallet use, and incineration for the NFR pallet. Similarly, glass fiber production, PP production, pallet production, transport, pallet use, and end of life incineration are modeled for the GFR pallet LCA. The study also includes disposal of intermediate wastes from fiber extraction processes. The study provides detailed comparative environmental performance in terms of energy consumption, emissions of 68 different chemicals to air, water and soil, and summary impact assessment using CML 92 [12] and Eco-indicator 95 procedures [9].[1] Selected comparative results from the study are summarized in Table 2.

Table 2
Comparative life cycle environmental performance of China reed reinforced, and glass fiber reinforced transport pallets [4]

Environmental indicator	Glass fiber pallet	China reed pallet
Cumulative non renewable energy use MJ	1400	717
Carbon dioxide emissions (kg)	73.1	42
Carbon monoxide (g)	74.3	54.6
NO_x air emissions (g)	513	349
Sulfur oxides (SO_x) air emissions (g)	289	163
Water emission—BOD (mg)	414	266
Water emissions—nitrates (g)	1.72	153
Water emissions—phosphates (g)	0.59	1.67
CML—human toxicity (kg 1,4 $dichl_{eq}$)	21.2	9.04
CML—terristrial ecotoxicity (kg 1,4 $dichl_{eq}$)	5250	4480
CML—Green house effect (kg $CO_{2\ eq}$)	75.3	40.4
Eco-indicator 95—carcinogenicity (10^{-7} kg PAH_{eq})	7.11	4.48
Eco-indicator 95—acidification (kg $SO_{2\ eq}$)	0.65	0.41

Overall, the NFR pallet results in significantly lower environmental impacts compared to GFR pallet, except for nitrate emissions to water associated with china reed cultivation. The study also reports results from sensitivity analyses with respect to: recycling at various percentages, pallet life, plastic content, and changes in transport distances, and finds that NFR pallet is environmentally superior under almost all scenarios. However, the environmental impacts of NFR pallet are worse, if the expected life of NFR pallet falls below 3 years compared to 5 years for the GFR pallet.

4. Drivers of superior environmental performance

These three studies show that in their specific applications, NFR composites are environmentally superior to GFR composites on most performance metrics. However, there are significant differences across these studies, in terms of the specific component/application being studied, material composition of the reference component as well as the NFR component, specific natural fiber chosen, production processes, boundaries and scope of the life cycle assessment, environmental impacts considered, and the data sources used. Also, due to space limitations, these published studies report only the final results of the comparative analyses, with very

[1] Eco-indicator is an aggregate index of environmental impact with weighting factors covering damage to resources, damage to ecosystem quality, and damage to human health, developed by Pre Consultants. For more details and updates see http://www.pre.nl/eco-indicator99/eco-indicator_99_introduction.html. CML 92 is a similar aggregate environmental impact index developed by the Center for Environmental Science (CML), University of Leiden, Netherlands.

Table 3
Nonrenewable energy requirements for production of different fibers (MJ/kg)

Nonrenewable energy requirements (MJ/kg)					
Glass fiber mat[a]		Flax fiber mat[a]		China reed fiber[b]	
Raw materials	1.7	Seed production	0.05	Cultivation	2.50
Mixture	1.0	Fertilizers	1.0	Transport plant	0.40
Transport	1.6	Transport	0.9	Fiber extraction	0.08
Melting	21.5	Cultivation	2.0	Fiber grinding	0.40
Spinning	5.9	Fiber separation	2.7	Transport fiber	0.26
Mat production	23.0	Mat production	2.9		
Total	54.7	Total	9.55	Total	3.64

[a] Source: Ref. [6], reproduced in Ref. [13].
[b] Source: Ref. [4], back up calculations obtained from the author.

little detail provided on the assumptions and intermediate calculations. Hence questions arise as to whether these findings can be generalized and if NFR composites are likely to be environmentally superior across other applications. Also if there are some general drivers of the relative environmental performance of GFR components and NFR components, that would allow us to make informed judgments without conducting detailed, time consuming and expensive life cycle analyses every time.

From these studies, we identify four general drivers of the relative environmental performance of NFR composites compared to GFR composites, which will help make such qualitative judgments. While Corbiere et al. [4] mention these as the major contributors to their finding that china reed pallets performed ecologically better than GFR pallets, we recognize these as environmental drivers that are also applicable to most other NFR composite materials.

4.1. Lower environmental impacts of natural fiber production compared to glass fiber production

Production of natural fibers results in less severe environmental impacts compared to production of glass fibers. Natural fiber cultivation depends mainly on solar energy, and fiber production and extraction use small quantities of fossil fuel energy. On the other hand, glass production and glass fiber production are both energy intensive processes depending mainly on fossil fuels. Table 3 shows the estimated life cycle non-renewable energy requirements for production of glass fiber and two natural fibers [4,6,13]. As can be seen glass fiber production requires 5–10 times more non-renewable energy than natural fiber production. As a result, the pollutant emissions from glass fiber production are significantly higher than from natural fiber production. Columns 2 and 3 of Table 4 tabulate the environmental impacts from glass fiber production and china reed fiber production processes [4]. Except for nitrate emissions associated with fertilizer use in china reed production, all other emissions are much lower for natural fibers. Increased nitrate emissions can lead to eutrophication of water bodies, which is a significant water quality problem in many areas. However, Corbiere et al. [4] find that life cycle eutrophication impacts of NFR composites are lower than life cycle eutrophication effects of GFR composites, when they include contribution of atmospheric NO_x emissions to eutrophication. These observations are likely to be valid across different natural fibers, since their production processes are very similar. Hence substitution of glass fibers by natural fibers of equal weight normally improves environmental performance of the component, with possible exception of local eutrophication effects.

4.2. Substitution of base polymer by higher volume percentage of natural fiber

NFR components typically will have a higher fiber volume fraction compared to GFR components for equivalent strength and stiffness performance, because glass fibers have better mechanical properties than natural fibers. This higher fiber volume fraction reduces the volume and weight fraction of the base polymer matrix used in the composite. The life cycle energy use and emissions from the production of most base polymers used in composites are

Table 4
Life cycle environmental impacts from production of glass fiber, china reed fiber, Epoxy resin, ABS and polypropylene

Environmental impact	Glass fiber[a]	China reed fiber[a]	Epoxy resin[b]	ABS[b]	Polypropylene[b]
Energy use (MJ/kg)	48.33	3.64	140.71	95.02	77.19
Carbon di-oxide emissions (kg/kg)	2.04	0.66	5.90	3.10	1.85
CO emissions (g/kg)	0.80	0.44	2.20	3.80	0.72
SO_x emissions (g/kg)	8.79	1.23	19.00	10.00	12.94
NO_x emissions (g/kg)	2.93	1.07	35.00	11.00	9.57
Particulate matter (g/kg)	1.04	0.24	15.0	2.90	1.48
BOD to water (mg/kg)	1.75	0.36	1200	33	33.94
COD to water (mg/kg)	18.81	2.27	51,000	2200	178.92
Nitrates to water(mg/kg)	14.00	24481	1	71	18.78
Phosphates to water (mg/kg)	43.06	233.6	220	120	3.39

[a] Source: Ref. [4], back up tables obtained from the author.
[b] Source: Ref. [8].

Table 5
Weight Reduction with natural fiber composites

Component	Source study	Conventional composite materials	Weight (g) of reference component	NFR materials	Weight (g) of NFR component	Weight reduction (%)
Auto side panel	[7]	ABS	1125	Hemp-Epoxy	820	27
Auto insulation panel	[5]	Glass Fiber—PP	3500	Hemp—PP	2600	26
Transport pallet	[4]	Glass Fiber—PP	15,000	China reed—PP	11,770	22

significantly higher than those associated with natural fiber production. For example, columns 4–6 in Table 4 show estimates of life cycle energy use and emissions from production of 1 kg of epoxy resin, ABS and PP extracted from APME eco-profiles [8]. These can be compared to the life cycle emissions associated with 1 kg of china reed fiber production shown in column 3 and it is obvious that energy use and emissions associated with base polymer production are significantly higher than those associated with natural fiber production. For example, PP production requires about 20 times more energy than natural fiber production and correspondingly the emissions are also higher. These observations are valid across most natural fibers and base polymers. Hence substitution of base polymer by higher natural fiber fraction will improve the environmental performance of NFR composites compared to equivalent GFR composites.

4.3. Lower use phase emissions due to weight reduction

This higher volume fraction of lower density natural fibers in NFR composites also reduces the weight of the final component. Table 5 shows the weights of equivalent GFR and NFR components from the three studies. As can be seen NFR components result in 20–30% reduction in weight.

Natural fiber composites are becoming popular in automotive applications because of this weight reduction. Lower weight components improve fuel efficiency and in turn significantly lower emissions during the use phase of the component life cycle. Eberle and Franze [14] estimate that the coefficient for reduction in fuel consumption on gasoline powered vehicles ranges from 0.34 to 0.48 l/(100 kg × 100 km) in the New European Driving Cycle, while the saving on diesel vehicles ranges from 0.29 to 0.33 l/(100 kg × 100 km). In other words, over the life time travel of 175,000 km an automobile, a kilogram of weight reduction can result in fuel savings of 5.95–8.4 l of gasoline or 5.1–5.8 l of diesel, and corresponding avoided emissions from production and burning of these fuels. The energy use and emissions associated with production and burning a kilogram of gasoline and diesel are shown in Table 6.

Table 6
Energy use and emissions associated with production and burning of a kilogram of gasoline and diesel

Fuel/environmental impact	Gasoline (/kg)	Diesel (/kg)
Energy use (MJ/kg)	48.9	49.9
Carbon di-oxide emissions (g/kg)	3343	3460
CO emissions (g/kg)	100.1	22.1
SO_x emissions (g/kg)	1.8	3.8
NO_x emissions (g/kg)	33.1	10.9
Particulate matter (g/kg)	0.3	0.34
BOD to water (mg/kg)	0.01	0.005
COD to water (mg/kg)	0.4	0.01

Source: Refs. [15,16].

By comparing the relative energy use and emissions associated with natural fiber production from Table 4 and emissions from fuels production and consumption in Table 6, it becomes obvious that for automobile applications, the avoided energy use and emissions from fuel efficiency improvement in the use phase will dominate the LCA results and greatly favor light weight natural fibers. Even in non-auto applications, reduced component weight can improve fuel efficiency and reduce emissions during transportation phase of the life cycle.

4.4. Energy and carbon credits from end of life incineration of natural fibers

Unlike glass fibers, natural fibers can be incinerated after the NFR component has served its useful life. For example, the energy credit associated with incinerating china reed fibers is estimated to be 14 MJ/kg. Some of these energy credits may be offset because less of base polymer is available for incineration. Similarly, incineration of natural fibers may increase air emissions, but lower mass of base polymer incinerated reduces air emissions. Hence the net effects on air emissions and energy recovery from incineration depend on the specific composition of components being compared. At the same time incineration of natural fibers theoretically results in no net addition to CO_2 emissions, because plants, from which natural fibers are obtained, sequester atmospheric carbon di-oxide during their growth, which is released during the combustion of natural fibers. Hence incineration of NFR composites leads to positive carbon credits and lower global warming effect.

5. Conclusions

Extant studies comparing life cycle environmental performance of natural fiber composites with glass fiber reinforced composites find that natural fiber composites are environmentally superior in the specific applications studied. We propose that NFR composites are likely to be environmentally superior to GFR composites in most applications also for the following reasons: (1) natural fiber production results in lower environmental impacts compared to glass fiber production; (2) NFR composites have higher fiber content for equivalent performance, which reduces the amount of more polluting base polymers; (3) lower weight of NFR composites improves fuel efficiency and reduces emissions during the use phase of the component, especially in auto applications; and (4) end of life incineration of natural fibers results in energy and carbon credits. A couple of caveats however are in order. First, fertilizer use in natural fiber cultivation results in higher nitrate and phosphate emissions, which can contribute to increased eutrophication in local water-bodies. One may have to tradeoff deterioration in local water quality against overall improvement in environmental quality. Second, the environmental superiority of NFR composites may vanish if NFR components have significantly lower operating life compared to GFR components.

The future of natural fiber composites appears to be bright because they are cheaper, lighter and environmentally superior to glass fiber composites in general. Future research should hence focus on achieving equivalent or superior technical performance and component life.

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