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Carbon storage potential in natural fiber composites

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Abstract

The environmental performance of hemp based natural fiber mat thermoplastic (NMT) has been evaluated in this study by quantifying carbon storage potential and CO_2 emissions and comparing the results with commercially available glass fiber composites. Non-woven mats of hemp fiber and polypropylene matrix were used to make NMT samples by film-stacking method without using any binder aid. The results showed that hemp based NMT have compatible or even better strength properties as compared to conventional flax based thermoplastics. A value of 63 MPa for flexural strength is achieved at 64% fiber content by weight. Similarly, impact energy values (84–154 J/m) are also promising. The carbon sequestration and storage by hemp crop through photosynthesis is estimated by quantifying dry biomass of fibers based on one metric ton of NMT. A value of 325 kg carbon per metric ton of hemp based composite is estimated which can be stored by the product during its useful life. An extra 22% carbon storage can be achieved by increasing the compression ratio by 13% while maintaining same flexural strength. Further, net carbon sequestration by industrial hemp crop is estimated as 0.67 ton/h/year, which is compatible to all USA urban trees and very close to naturally, regenerated forests. A comparative life cycle analysis focused on non-renewable energy consumption of natural and glass fiber composites shows that a net saving of 50 000 MJ ($\sim$ 3 ton CO_2 emissions) per ton of thermoplastic can be achieved by replacing 30% glass fiber reinforcement with 65% hemp fiber. It is further estimated that 3.07 million ton CO_2 emissions (4.3% of total USA industrial emissions) and 1.19 million m^3 crude oil (1.0% of total Canadian oil consumption) can be saved by substituting 50% fiber glass plastics with natural fiber composites in North American auto applications. However, to compete with glass fiber effectively, further research is needed to improve natural fiber processing, interfacial bonding

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and control moisture sensitivity in longer run.

Keywords: Carbon storage; Carbon dioxide emissions; Green house gases; Natural fiber composites; Hemp fiber; Mechanical performance; Mat-reinforced; Auto applications

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1. Introduction

Over the last few years, ecological concern and global warming has initiated a considerable interest in using natural materials to produce green products and reduce anthrapogenic carbon dioxide emissions by all possible means. Kyoto protocol has further highlighted this issue by which many countries including Canada has committed to reduce combined CO_2, CH_4 and N_2O emissions by 6% below 1990 levels between 2008 and 2012. Fossil fuel combustion is the main source of worldwide carbon dioxide emissions, which account for more than 99% of all green house gases (GHG). Unfortunately North America had 28.2% share (Canada 2.2%, USA 26%) of total world CO_2 emissions ($\sim$6 billion metric ton Carbon equivalent) based on energy related fossil fuel consumption according to year 2000 carbon dioxide fact sheet (Emissions of greenhouse gases in US). In the present scenario, natural fibers have excellent potential to reduce not only CO_2 emissions but also save non-renewable resources by substituting glass fiber reinforcements in automobile thermoplastics.

Traditionally, glass fibers/wool have been extensively used as building insulation material and reinforcement in auto sector thermoplastics. However, environmental performance of glass fiber mat thermoplastics (GMTs) has several drawbacks due to extensive energy consumption and potential health risks during production and handling. Glass fibers cause severe abrasion to process equipment and their composites may transform into sharp splints during collision causing extra injuries to passengers. Moreover GMTs are non-recyclable and their incineration generates clinker like mass that is hard to dispose off except land filling.

On the other hand, natural fibers are being explored more extensively by research institutions and automobile companies as environmental friendly alternative for the use of glass fibers. Most of the bast fibers being studied are obtained from naturally growing plants of flax, hemp, and kenaf. These fibers are renewable, non-abrasive to process equipment and can be incinerated at the end of their life cycle for energy recovery as they posses a good deal of calorific value. They are also very much safe during handling and less suspected to affect lungs during processing and use.

Automotive applications represent the best opportunity for natural fibers thermoplastics due to some of distinctive advantages over glass fibers, like, low weight (35–40% less as compared to glass fiber), low price, better crash absorbance and sound insulation properties. Some of the potential applications in this field are: door and instrument panels, package trays, glove boxes, arm rests, and seat backs.

There is an interesting comparison (Van Voorn et al., 2001) about tensile strength of various natural fibers and regenerated cellulose (rayon) as a reference. The tensile strength of flax and hemp falls between 600 and 800 MPa, which is much higher than other natural fibers. In terms of density (Garkhail et al., 2000), natural fibers weigh only 40% that of glass fibers, thus having competitive advantage in automobile applications.

Unfortunately, most of the work in this area has been done on the evaluation of mechanical performance of natural fiber composites and little data is available to gauge the environmental advantages of these materials especially the carbon storage potential of renewable plants. In literature Van Voorn et al., 2001 the mechanical properties of glass and flax fiber sheet molded composites based on wet-laid process have been compared and it is shown that stiffness of flax fiber composites is comparable or even better whereas, flexural and tensile strength properties are slightly lower. However, impact strength of flax fiber composite is only 3–7 kJ/m^2 as compared to 40 kJ/m^2 for glass fiber composite. Similar comparisons have been reported by other researchers (Garkhail et al., 2000; Kristina Oksman, 2000) while using film-stacking technique.

This study has been focused primarily on native hemp fiber of Ontario and main objective was to investigate mechanical properties and environmental performance of finished natural fiber mat thermoplastic (NMT) and compare the results with commercially available glass fiber products. The effect of compression ratio on strength and consolidation has also been reported in this work.

2. Experimental

2.1. Materials

The polypropylene (PP) matrix was provided by a Canadian company in the sheet form having a thickness of 101 micron. As per supplier's data, the ultimate tensile along TD is 37 MPa whereas secant modulus is 0.8 GPa.

The non-woven needle punched mats of hemp fiber were arranged from a commercial source. The hemp fiber content by weight was 80% while the rest was PP. The average basis weight of these mats was 265 g/m$^2 \pm 8$.

2.2. Manufacturing of composite sheets

Representative samples of composites were manufactured by film-stacking method. First the non-woven mats of hemp of approximately 210 × 210 mm were cut and dried for 2 h at 105 °C in an electric oven. Immediately after this pre-dried non-woven fiber mats and PP films were stacked alternately for impregnation in a hydraulic press, Wabash, having 50-ton capacity with air/water cooling arrangement. The heating time was 10 min at 205 °C temperature. To study the effect of compression different pressures (14–60 bar) were used and few samples were made by using spacers between the press plates. The press was cooled at the end of heating/impregnation cycle to 50 °C in about 4 min before completing the compression molding process.

To have smooth surface of sheets and prevent sticking of PP/fibers on hot press plates, Dupont Mylar (polyester) films were used at top and bottom of stacked blanks. The molded NMTs had thickness between 1.3 and 2.9 mm and base weight ranging from 570 to 2880 g/m^2.

2.3. Testing

2.3.1. Flexural and tensile testing

Flexural test (3-point bending) was conducted on Zwick-z100 tester according to standard test procedure D-790. Specimens were 12.5 mm wide and 150 mm long. The thickness varied from 1.1 to 2.9 mm and machine speed was set at 10 mm/min. The tensile testing was done on same machine and specimens were prepared according to test method D-638 while the crosshead speed was maintained at 2 mm/min.

2.3.2. Impact energy

Izod ‘notched’ impact testing was carried out on Tinius Olsen (92T Impact T.M) test machine according to ASTM D 256. The specimens had depth of 12.7 mm and length of about 64 mm. The testing machine had inbuilt processor to calculate absorbed energy in J/m. However, impact energy in J/m^2 was also calculated by dividing the net value of absorbed energy with product of measured width and depth under the notch.

2.3.3. Density profiling

An X-ray density profiler, QMS (QDP-01X) was used to study the effect of different compression ratios on molded composites and have accurate density measurements. This machine has capability of scanning 1/1000 of an inch and specimens had dimensions of 50 × 50 mm with varying thickness from 1.1 to 2.9 mm. The scanning was done through five pre-determined zones across the thickness of specimen.

3. Mechanical performance

3.1. Mechanical properties

Significant results have been observed by achieving maximum flexural and tensile strength of 63 and 47 MPa, respectively as shown in Fig. 1, without using any binder aid. Unfortunately no reference data is available for hemp based NMTs to compare this result, however, similar values are reported (Van Voorn et al., 2001; Garkhail et al., 2000; Kristina Oksman, 2000) for flax based composites while using 3–5% maleic-anhydride binder in some cases.

More interestingly, these results correspond to density values from 0.90 to 0.96 g/cm^3, which is about 56% less as compared to glass fiber composites as mentioned in reference book (Callister, 2000). It means that specific strength and stiffness

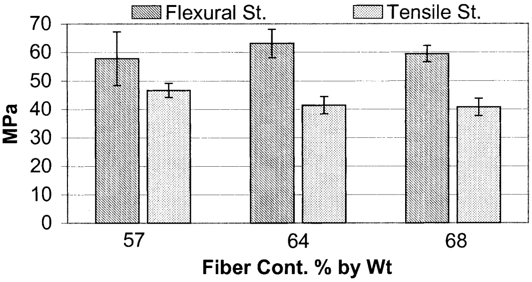

Fig. 1. Flexural and tensile properties of hemp based NMTs.

properties of these NMTs can be very compatible to traditionally used GMTs in auto industry with an added advantage of low weight.

3.2. *Effect of compression*

3.2.1. *Tensile and flexural strengths*

A definite trend of increase in tensile/flexural values has been shown in Fig. 2 with corresponding increase in molding compression for two different fiber contents while keeping the other conditions almost same. A tremendous increase of 23 times was observed in flexural strength for 67% fiber content NMT while increasing the compression ratio from 42 to 77%. For 64% fiber content NMT, an increase of 6 times in flexural value was obtained against an increase of compression ratio from 55 to 79%.

$$\text{Compression ratio} = (t_{i\_} t_f)/t_i$$

where t_i is initial combined thickness of hemp mats and PP films before consolidation and t_f is final thickness of NMT sample.

3.2.2. *Density profile (consolidation)*

Similarly, higher compression produced a more uniformed density product as shown in Fig. 3. All this can be attributed to void spaces present in original fiber mat and poor fiber-to-fiber bonding under low compression. However, further testing is

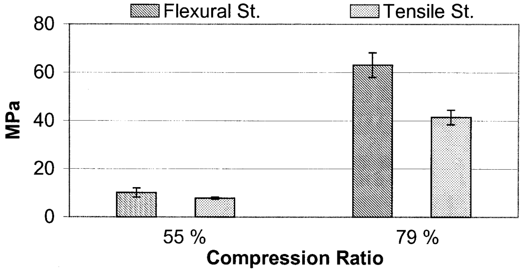

Fig. 2. Compression effect on flexural and tensile properties for 64% hemp fiber NMT.

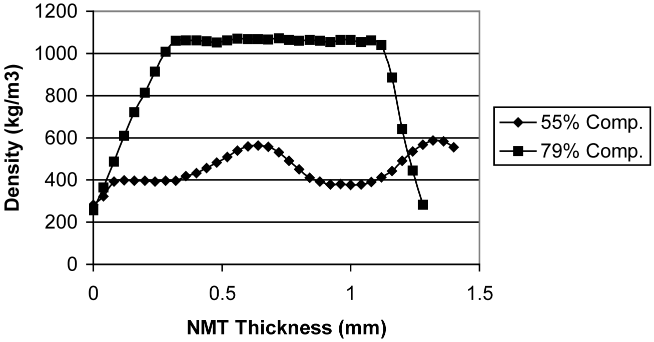

Fig. 3. Compression effect on density for 64% hemp fiber NMT.

in progress to identify optimum values of *pressure* and *fiber content* for maximum strength properties.

3.2.3. Impact energy

We have been able to get impact energy of 84,111 and 154 J/m for NMT samples containing 68, 57 and 70% hemp fiber by weight, respectively under different impregnation pressures as shown in Fig. 4. Similar values have been reported (Garkhail et al., 2000) in literature for flax fiber composites while using 5% binder. Therefore, it is anticipated that with further optimization and use of proper binder, we will be able to enhance interfacial bonding between fiber and matrix yielding much better results in overall mechanical behavior.

A comparison of tensile strength has been shown in Fig. 5 for hemp, flax and glass reinforced mat thermoplastics. It may be noted that except for hemp based NMT, all the other data is taken from literature.

The Flax (Danflax) data is taken from work of Kristina Oksman, 2000 where fiber content is 50% by weight. Glass fiber laminate data belongs to commercially available products from Azdel Inc. with fiber content of 32%. This comparison shows that hemp based NMT has compatible strength to that of flax based thermoplastics. However higher strength of GMT can be attributed to better strength of glass fibers, 3450 MPa (Callister, 2000), compared to hemp and flax

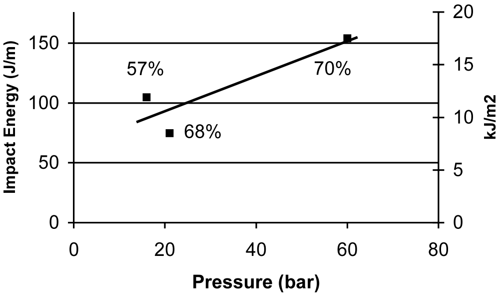

Fig. 4. Effect of compression and fiber content on impact energy.

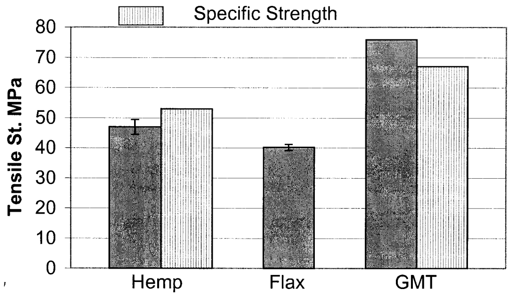

Fig. 5. Tensile strength of different NMTs and GMT.

fibers. Further, NMTs tend to be more anisotropic due to inherited physiological characteristics of natural fibers.

4. Environmental performance comparison

4.1. Scope

This study concentrates on quantifying carbon storage potential of hemp fibers used in NMTs by estimating dry weight biomass of these fibers. This estimation can give some idea about carbon sequestering capability of natural fibers, which is a key factor in combating increasing levels of atmospheric carbon dioxide. Overall energy balance is also included in the scope for production and incineration of similar amount of natural and glass fiber composites for auto industry. The base unit is taken as one metric ton of hemp based thermoplastic (65% fiber content) and same amount of glass fiber (30% fiber content) composite.

4.2. Carbon storage estimation

Industrial hemp (Cannabis sativa) is grown under license in many parts of Ontario and specified varieties contain less than 0.3% THC (delta-9 tetrahydrocannabinol) a hallucinogic ingredient (Baxter and Scheifele). Bast fiber yield is usually 15–25% and plants may grow up to 2–4 m without branching with maturing time as 60–90 days. The stem of plant has an outer bark with long and tough bast fibers having very low lignin content ($<9\%$) and high tensile strength (900 MPa)(Rowell et al., 2000). These fibers are usually used for cording, textile and paper manufacturing. The core of stem contains hurds (short fibers), which are used mostly in composite for different applications and also for animal bedding and garden mulch. Due to very rapid growing, the biomass accumulated by hemp crop has significant effect in absorbing atmospheric CO_2.

In Fig. 6, a value of 325 kg of carbon stored by biomass of hemp fibers is estimated in 1 ton of composite having 65% fiber content. All the base data regarding hemp growth is taken from fact sheet of Ministry of Agriculture and

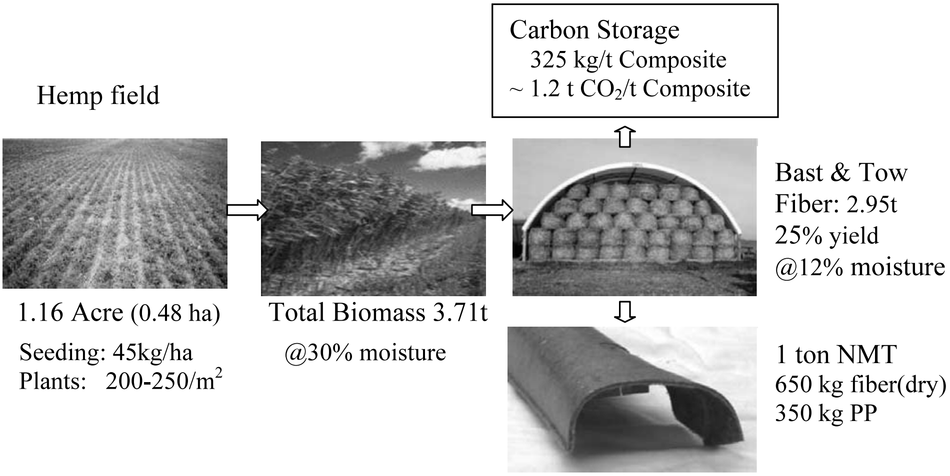

Fig. 6. Schematic of industrial hemp (Cannabis sativa) growth and carbon storage potential in 1 ton of thermoplastic containing 65% fiber content. Photos: courtesy of The Hemp Report Canada. Volume 3, Issue 17, 2001. http://www.hempreport.com and Hempline. http://www.hempline.com.

Food, Ontario (Baxter and Scheifele). Now if we concentrate on auto sector, which is the main target of this research study, the projected consumption of natural fibers in the same sector by 2005 in North America is estimated as 45 million kg (K.Line and Company, 2001), which translates into final product of 69 million kg (65% fiber content); 3.8 kg/vehicle, only 10% of the current consumption of glass fiber plastics per vehicle. However, even with this conservative estimate, the overall carbon storage potential (22.5 million kg) in this amount of composite products is very significant as shown in Fig. 7. The total projected vehicle sale in North America in 2005 is reported as 18 million (DesRosiers Automotive Consultants Inc.).

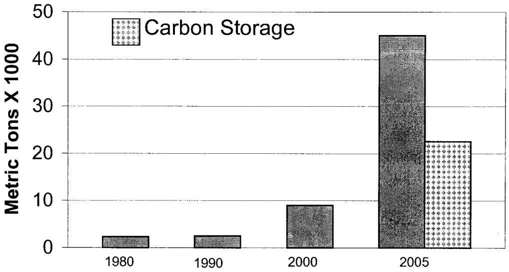

Fig. 7. Historical and projected demand of natural fibers (excluding wood fibers) in North America. 1980–2000 represents all applications. 2005 depicts only auto applications. (K.Line and Company, 2001; Automotive Learning Center).

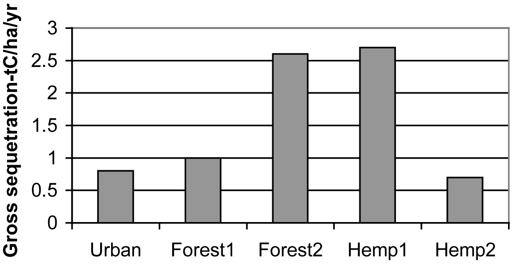

Fig. 8. Average gross carbon sequestration by urban/forest trees and hemp plants.

4.3. Carbon sequestration: industrial hemp versus trees

A comparison of average gross carbon sequestration/ha/y is shown in Fig. 8. The data about urban and forest trees (USA) is taken from work of Nowak and Crane, 2002 whereas hemp plants data is estimated by authors of this study. Carbon storage in each case is calculated by multiplying total dry weight biomass by a factor of 0.5. Forest 1 represents 25-year-old naturally regenerated spruce-fir stock and Forest 2 belongs to 25-year-old genetically improved loblolly pine plantation on a high yield site. Hemp 1 data takes into account the entire biomass, which is usually twice that of trees. However some of the carbon stored in this biomass is turned back to atmosphere as CO_2 due to biodegradation of leaves and roots and some less durable products like mulch and animal bedding. The true long-term carbon stored is represented by Hemp 2 which is bast fiber used for durable products including composites, textile, cordage, twine and specialty paper.

4.4. Compression versus carbon storage in NMTs

Although current utilization of natural fibers in thermoplastics for various applications is about 50% by weight, but this ratio can be increased safely by further process optimization without compromising strength properties. Increase in fiber content serves dual purpose. First the amount of carbon stored for substantially amount of time is increased and secondly more fiber mean less amount of thermoplastic which ensures considerable savings in overall energy consumption and CO_2 emissions. It is interesting to mention here that energy required per unit weight production of PP is almost double of glass fiber.

In this study the maximum flexural strength (63 MPa) achieved is at 64% fiber content and compression ratio of 79%. However, more or less same results are obtained at two different sets of conditions as shown in Fig. 9. It is evident that by increasing fiber content from 57 to 70% with an increase in compression ratio, a net increase of 22% carbon storage is achieved.

Further research is required to find optimized value of compression and fiber content at which maximum mechanical performance of composite is achieved.

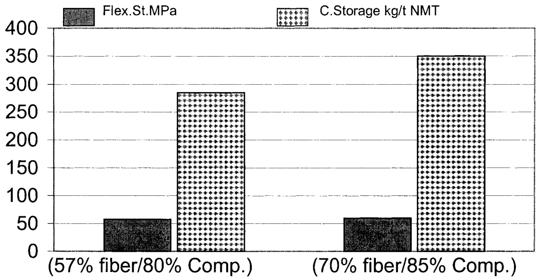

Fig. 9. Effect of compression and fiber content on carbon storage potential of NMT.

4.5. Energy consumption comparison: hemp versus glass fiber composites

The energy consumption through the burning of non-renewable fossil fuels has major effect in elevating atmospheric CO_2 levels from 310 ppm (1950) to 360 ppm (2000) which represents a drastic situation by an addition of 6.6 billion metric tons of carbon to the atmosphere annually (Emissions of greenhouse gases in US). The per capita CO_2 emissions (ton carbon/year), the main component of GHG, in USA (5.6) and Canada (5.1) is the highest among all countries including Japan (2.5) while the world average is only 1.1 (World per capita carbon dioxide emissions from fossil fuels).

On a percent-of-shipment basis, the glass industry ranks at top being the most energy-intensive industry. The total annual shipments from all US glass industry is about $27 billion with purchased energy cost as $1.4 billion (Glass industry analysis brief) about 5% of shipments. In year 2000, the CO_2 emissions associated with glass industry was about 0.18 million metric tons in USA and glass fiber had a share of 15% of this amount. The total industry related CO_2 emissions were 71 million metric tons (US Carbon dioxide emissions from industrial processes, 1990–2000).

The glass fiber manufacturing involves two major steps. First the molten glass is made by blending quarry raw materials (sand, kaoline, limestone, colemanite, etc.) and heating in refractory furnace at 1500–1700 °C. In second step, the liquid glass is passed through micro-fine bushings and simultaneously cooled to produce filaments of 5–25 μm diameter. The filaments are drawn together to form strand or roving as per requirement after coating with ‘size’. The fiberglass used in composite reinforcement is called E-glass (electrical), which is low in alkali content and has good tensile and compressive strength.

In Table 1, a detailed comparison is shown for energy consumption between hemp based and glass fiber composites. It is very difficult to get real time energy data for such products, therefore some assumptions and references are used mentioned below Table 1. The main reference in this regard is the work of Corbiere-Nicollier et al. 2001 based on life cycle assessment of biofibers replacing glass fibers in plastics. The heat value of hemp fibers is estimated by calculating total carbon content in 1 ton of composite and multiplying with standard value of 7.83 kcal which is heat energy

Table 1
Overall energy consumption schedule for NMT and GMT

Quantity (1 metric ton)	NMT (65% fiber)	MJ	GMT (30% fiber)	MJ
(a) Materials				
	Hemp cultivation	1340	Glass fiber production	14 500
	PP production	35 350	PP production	70 700
	Total	36 690	Total	85 200
(b) Production				
	Composite	11 200	Composite	11 200
(c) Incineration				
PP incineration				
	Energy required	117	Energy required	234
	Energy released	−7630	Energy released	−15 260
Hemp fiber incineration			*Glass fiber incineration*	
	Energy required	1108	Energy required	516
	Energy released	−10 650		
	Net	−17 055	Net	−14 510
(d) Balance				
	Gross energy required	49 115	Gross energy required	97 150
	Energy released	−18 222	Energy released	−15 260
	Net energy required	30 800	Net energy required	81 890

Sources: Hemp cultivation: Fuel consumption/acre: 29 l. Fact sheet on growing industrial hemp in Ontario. Ministry of Agriculture and Food (Baxter and Scheifele). One barrel crude oil equivalent to 5.8 million BTU. Department of Energy, USA (Approximate heat content of crude oil, crude oil and products, and natural gas plant lipids, 1949–2001). Specific energy consumption for materials (glass fiber, PP), composite production and incineration: Corbiere-Nicollier et al., Life Cycle Assessment of Biofibers replacing Glass Fibers As Reinforcements in Plastics. (Corbiere-Nicollier et al., 2001). Study based on China Reed and glass fiber thermoplastic transport pallets.*Assumptions*: The average fiber content in glass fiber plastics (auto sector) is taken as 30%, although in commercial grades it varies from 22 to 40%. The energy required to incinerate hemp fiber is equivalent to china reed fiber. The energy required for hemp fiber cleaning/processing not included in this study.

liberated by combustion of 1 g of carbon mass. The heat value thus estimated for hemp fiber comes out as 16 338 kJ/kg.

4.6. Results and discussion

4.6.1. Carbon storage

The annual carbon sequestration estimation for hemp is based on only one crop per year. But in some warm areas like Puerto Rico, two or even three crops per year have been reported. In this scenario the carbon sequestration rate of fiber-based hemp crop can surpass both urban and forest tree plantations. However, the main solution in maintaining good quality and better yield of hemp is ‘crop rotation’. Fortunately, rotation of hemp with wheat (England) and soybean (Ontario) has been reported successfully in literature with reduced pesticide demand for secondary crop. The second aspect is useful life of hemp based composites. With ongoing research activities in various institutes and industry in this area it may be assumed that life span of natural fiber composites will reach to the levels of glass fiber products in near future. In that case the total amount of carbon stored in such products will absolutely increase on long-term basis.

4.6.2. Energy savings

From Table 1, it is evident that natural fiber composites consume only 37% energy in their entire life cycle as compared to glass fiber composites. In other words for a same amount of product 60% savings is achieved.

The maximum savings in energy, Fig. 10, is achieved due to reduction in PP use by maintaining high ratio of hemp fibers followed by altogether substitution of glass fiber which require very high energy consumption for their production. The low savings in terms of incineration can be attributed to high incineration value of PP compared to hemp fiber as shown in Table 1. The net saving of around 50 000 MJ by using 65% hemp fibers instead of 30% glass fibers in thermoplastic matrix not only saves non-renewable fossil fuels to a great extent but also helps in reducing CO_2 level in the atmosphere.

4.6.3. Carbon dioxide emissions and savings

4.6.3.1. Materials and manufacturing. Fig. 11 shows CO_2 emissions in t/t of composite for both natural and glass fibers. These values are estimated by converting energy into CO_2 emissions using standard conversion factors for different fossil fuels. Oil is assumed as base fuel for this study, which emits 75% CO_2 emissions, compared to coal (Greenhouse gases, global climate change, and energy). The average value of carbon dioxide emission for coal in 1999 is mentioned as 208 pounds per million Btu (Carbon dioxide emission factors for coal). The heat energy liberated by incineration of hemp fiber and PP is also added in non-renewable energy requirements to make calculations simpler. The results demonstrate a net reduction in emissions of 3 t CO_2/t of product if glass fibers are substituted by hemp fibers and consequently 1.16 m^3 (1160 l) of crude oil is saved for same amount of product.

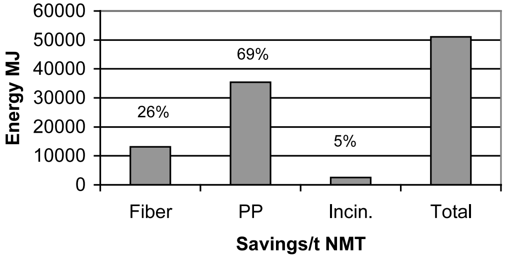

Fig. 10. Energy savings per ton NMT by substituting glass fiber/PP and incineration.

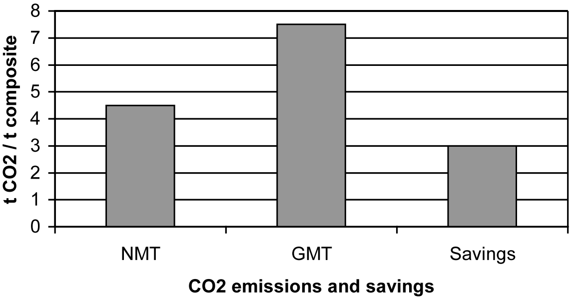

Fig. 11. CO_2 emissions per ton composite and reduction in emissions by substituting glass fiber with hemp fibers.

All these savings are based on 1 ton of composite only. Now if we consider projected consumption of all natural fibers (excluding wood) by 2005 as 45 million kg in auto sector and assuming more or less same amount of biomass in all fibers (hemp, flax, kenaf) and 65% fiber ratio in thermoplastic then annual CO_2 reduction possible is 0.135 million tons.

4.6.3.2. Weight reduction. The second important aspect in curtailing carbon dioxide is overall reduction in weight of vehicle by substituting glass fibers with natural fibers because ultimate use of these products depends on specific strength properties and density. The average specific gravity of hemp based thermoplastic achieved in this study is 0.9 whereas for commercial glass fiber composites (30% fiber) being used in automobiles this value is around 1.14. It shows 21% weight reduction for a particular molded part but to gauge the true impact of this we must know the overall weight reduction in car. According to current estimates (DesRosiers Automotive Consultants Inc., Automotive Learning Center and Corporate news) an average car in North America (1479 kg weight) has about 38 kg of glass fiber plastics. By substituting this with natural fiber products, a net reduction in weight of car comes out as 0.54%. Now taking average fuel consumption of 1 l/10 km and assuming 7% increase in fuel efficiency for 10% weight reduction (Automotive Learning Center), the total savings in CO_2 emissions are estimated as 4.13 million ton/year. The average mileage/year of all vehicles in North America is reported as 4352 billion km by DesRosiers Automotive Consultants Inc. during the period of 1990–99.

Table 2 represents a hypothetical but possible scenario in which 50% glass fiber products in auto sector applications have been replaced by natural fiber (hemp) composites in North America. A base figure of 0.203 million ton of glass fiber reinforcements in auto industry for year 2000 (Corporate news) has been taken to calculate total amount of glass fiber composites assuming 30% fiber loading and hemp based composites are based on 65% fiber loading. All estimates are based on year 2000 figures.

The results in Table 2 show a tremendous potential of natural fibers as a mean to control not only green house gas impact but also save non-renewable resources to great extent. However, to reach at sustainable production levels and compete with

Table 2
Annual potential savings in CO_2 emissions and non-renewable resources by replacing 50% glass fiber composites with natural fibers in auto sector applications

	Savings	
	Emissions Carbon dioxide (million ton)	Resources Crude oil (million m^3)
Materials/manufacturing	1.01	0.39
Weight reduction (by saving fuel)	2.06	0.8
Total	3.07	1.19
% of total Canadian fossil fuel emissions[a]	0.5	–
% of total Canadian oil consumption[b]	–	1.0
% of total US industrial emissions[c]	4.3	–

[a] World carbon dioxide emissions from the consumption and flaring of fossil fuels, 1991–2000.
[b] World petroleum consumption, 1991–2000.
[c] US Carbon dioxide emissions from industrial processes, 1990–2000.

glass fiber products in mechanical performance and durability, a multidimensional research is required to improve fiber processing, interfacial bonding and control moisture sensitivity of natural fiber composites in the long run.

5. Conclusions

The results in this study show that use of natural fibers in thermoplastics have great potential to act as sustainable ‘sink’ for atmospheric carbon dioxide and at the same time saving non-renewable resources. The importance and urgency to expedite research activities in this area can be further augmented by the fact that consumption of different kinds of composites is growing very rapidly in various applications. The use of plastic and composites has experienced tremendous growth of 1300% (Gerard Van Erp) during the last four decades with main area of application being land transportation, around 500 000 metric tons in 2000 (Summerscales et al., 1995). In this scenario, replacing even 20–25% glass fiber plastics with natural fiber composites can make a lot of difference for industrialized states, specially North America, to curtail not only GHG emission but also to claim ‘carbon credit’ for these fibers. The monetary value (Nowak and Crane, 2002) associated with carbon storage potential of hemp based thermoplastic can be estimated as C$ 11.0/t composite. The significant energy savings of 60% per ton of product by using natural fiber reinforcements is possible through four means; reducing use of PP by using higher proportion of natural fibers, actual substitution of high energy consuming glass fibers, low weight of natural fiber composites and finally saving in land filling efforts. The use of proper compression during molding can be another key factor to add maximum amount of natural fibers without lowering mechanical strength and other properties. This can further increase the carbon storage potential of NMTs.

The mechanical performance of hemp based NMT reported in this study is achieved without using any binder aid. The results are compatible with flax based and glass fiber thermoplastics in tensile properties. However, to take the full advantage of excellent strength of individual natural fibers further research is needed in finding better and novel ways for fiber processing. The next theme of this research project is to improve interfacial bonding and dimensional stability of hemp based thermoplastics, which are key factors to enhance impact properties and durability of these products.

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