Modelling Carbon Footprint, Emission, and Sequestration of Kenaf Cultivation and Fiber Processing and Utilization into Automotive Components

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This study aimed to model carbon footprint, carbon dioxide sequestration, and emissions from kenaf cultivation as well as utilization of core and bast as biomaterials in the automotive industries and their environmental implications. It also considers the selection of suitable processing methods to improve the environmental performance of automotive parts. The data were obtained from three areas, and each area was divided into three cultivated sub areas for the carbon footprint model. Data regarding the conversion of kenaf to fibre when using kenaf high decorticator machines were provided from Kenaf Processing and Marketing Centre (CMPC) in Malaysia. The results showed that the total estimated quantity of carbon footprint of kenaf cultivation in the studied areas as well as the farms was about 0.750 tonne CO_2/tonne. In addition, the total estimated quantity of carbon sequestration of automotive components in the studied states as well as the district was approximately 180,000 tonne CO_2/tonne/hectare/year in addition to carbon sequestered by soil in hectare of cultivated kenaf. The practices of kenaf cultivation, processing, and utilization into automotive components is essential for the environment and will assist in the mitigation of climate change risks.

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INTRODUCTION

Natural fibres such as flax, hemp, jute, or kenaf are frequently utilized into technical applications, particularly in biocomposites in automotive interiors and insulation. These natural fibres have a much lower carbon footprint than their counterparts, glass, and mineral fibres. The production of 1 tonne of glass fibres shows a carbon footprint of about 1.7 to 2.2 tonne CO_2-eq, whereas natural fibres only have a carbon footprint of about 0.5 to 0.7 tonne CO_2-eq per tonne of the raw material. This is only one third of the carbon footprint of glass fibres. Even as the initial advantage decreases in further processing, natural fibre composites have a 20 to 50% lower carbon footprint compared to glass fibre composites (Barth and Carus 2015).

The carbon footprints of the different natural fibres are not very different from each other. In the range of uncertainty, the carbon footprint of non-woven products in the automotive or insulation sector is about 750 kg of $CO_{2\text{-eq}}$ per tonne of natural fibre material for all four natural fibres. Jute and kenaf show lower emissions during cultivation, harvesting, and decortication because of manual processing.

Fertilizers have a high share in the total calculation of emissions. Therefore, substituting mineral fertilizers by organic fertilizers leads to a lower carbon footprint of 650 kg of $CO_{2\text{-eq}}$ per tonne of natural fibre. Using organic fertilizer is only possible if the crop and the region are suitable. The data on GHG emissions in the production of natural fibres still show some gaps, especially for water and field retting, where no solid data are available (Barth and Carus 2015).

Kenaf is an herbaceous annual plant found in Asia and Africa. It has a single line stem encompassing two parts, an outer fibrous bast and an inner core. Kenaf grows speedily, reaching 4 to 5 m in height and 25 to 35 mm in diameter in a 4- to 5-month growing season. Kenaf cultivation provides a high biomass production, a wide growth area, and strong adaptability to the environment (Monti and Alexopoulou 2013).

Several studies have been carried out to emphasize zero-emission models for the bast fibers industries for purposes of renewable products. Furthermore, income from carbon trade in natural fiber production can reach the local producer due to the local environmental and socio-economic improvements (Roy *et al*. 2019). As stated by van Dam, (2008), in the value chain of any fiber crop production and processing, there were many environmental impacts that can be investigated. The impact on the environment depends on the produced weight of fiber products and the size of the end-use market.

Greenhouse gas (GHG) emission in the form of carbon (C) and related gases in the atmospheric layer is one of the most important areas of investigations for the environmentalist. The greatest amount of carbon is released to the environment because of fossil fuels used in automotive engines. Additionally, the reports of environmentalists in COP27 year 2022 indicated that there were 1,446 billion cars on the earth that year. It was noted that road transport causes about 12% of global carbon dioxide emission. Nevertheless, tropical ecosystems sequester 340 billion tons of carbon, and there are several methods used to calculate the emitted and sequestrated carbon that can assist in the estimation of carbon dioxide for its importance and enrichment of the knowledge in this issue (Kongsager *et al.* 2013).

The carbon released from production of bast and core includes input levels, field processes, and carbon sequestration rates from soil tests and can be obtained relative to periods of time. Carbon release values (tons of C/ha) from direct energy, alive or indirect, used for the application of fertilizers and chemicals were estimated along with evaluations from direct energy used in farm operations such as application of herbicide and fertilizers, labor, planting, and harvesting (Williams and Association 2002; Lam *et al*. 2003). Singh *et al.* (2018) studied the carbon footprint of natural fibers crops such as jute, flax, kenaf, and sun hemp. Their investigation illustrated that all the fibres crops did not differ significantly. Thus, their results of carbon footprint were 566, 520, 445, and 423 kg CO_2-eq/tonne of fibre for jute, flax, kenaf, and sun hemp, respectively. The carbon-based sustainability index for jute (2.27) and kenaf (2.07) were highest due to better carbon use efficiency. The sustainability index of flax was negative (-0.67) due to higher carbon emission. Fertilization and fibre processing contributed most to GHG emissions. Overall, the carbon footprint of bast fibres was 20 to 50% inferior to that of synthetic/artificial fibres.

EXPERIMENTAL

Data Collection

Methods of processing kenaf stem into core and bast and their carbon stored

The data used in this study were obtained from the scenarios of the selected three kenaf farms, which are here denoted as A, B, and C. Each area was divided into three cultivated areas. Data regarding the conversion of kenaf to fibre when using kenaf high decorticator machines were provided from Kenaf Processing and Marketing Centre (CMPC) in Malaysia, and the data were used to convert the kenaf cultivated in the three areas and their subareas into bast and core. In this section, the quantitative data of kenaf processing, such as the percentage of kenaf stem parts when converted to fibre, was obtained from the kenaf factory, which was simulated from the daily data record for a period of one month regarding the processing of kenaf using the above-mentioned decorticator. In addition, the simulated data were used to estimate how much core, bast, and waste can be produced from one ton of kenaf when processed to produce the industrial fibre parts. To convert the processed fibre into stored CO_2, the whole processed raw kenaf fibre material was multiplied by 1.27, which is equivalent to the carbon dioxide stored by kenaf fibre (kgCO_2/kg), as reported in Barth (2015).

Estimation of Kenaf Fibre Carbon Footprint

Barth (2015) estimated a carbon footprint of 0.5 to 0.7 tonne $CO_{2\text{-eq}}$ per tonne of natural fibre (until the factory gate, excluding transport to the customer). This value was used to determine the initial carbon footprint data of the selected area. The carbon footprint C/tonne/Ha was estimated by use of Eq. 1.

$$\text{Carbon footprint of kenaf core} = \text{kenaf core weight} * 0.6 \qquad (1)$$

Three scenarios of kenaf production were assumed (10, 12, and 15 ton/ha), as reported in the work of Abdelrhman *et al*. (2016), Paridah *et al.* (2017), and Abdelrhman (2022). This was done by considering the average weight of dry matter of kenaf and using available data to estimate the fibre production per the studied area using the method applied in the cited work (Abdelrhman *et al*. 2016; Paridah *et al.* 2017; Abdelrhman 2022).

Carbon Dioxide Emission and Sequestration of Kenaf Cultivation

Carbon dioxide sequestration and emission was estimated in the four Malaysian states and their districts, as shown in Fig. 1, using published analytical methods (Abdelrhman *et al*. 2016; Paridah *et al.* 2017; Abdelrhman *et al*. 2021, 2022).

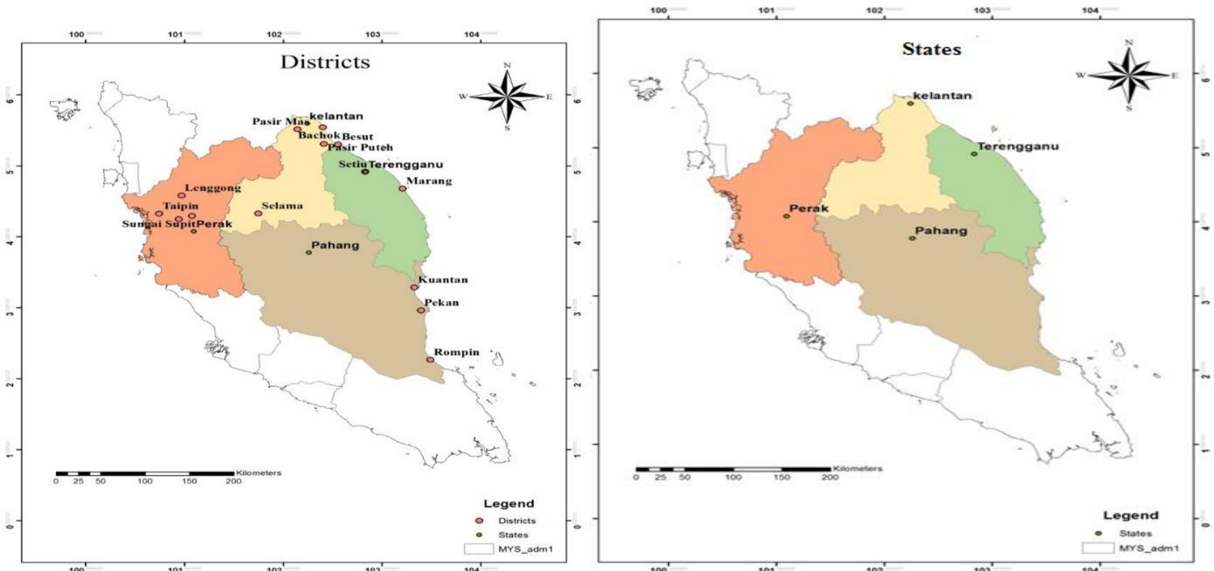

Fig. 1. Map of Kenaf Districts and States in Malaysia

Estimation of Kenaf Carbon Emission and Sequestration

Kenaf cropping sequestering carbon in the soil was equivalent to one ton per hectare in a rotation. It also emitted carbon in the form of CO_2 into the atmosphere from the combustion of diesel used in field operations, such as tillage, fertilizer and herbicide application, planting, and harvest. Equation 2 was used to estimate carbon equivalent emissions due to direct energy consumption for farm operations. The fuel usage per hectare varied, depending on the field operation activities.

$$\text{Carbon emissions} = \text{Fuel consumption} \times 87\%\ \text{C} \times \%\ \text{occurrence} \quad (2)$$

It was assumed that diesel fuel contains 87% Carbon as shown in the model.

The carbon emission of energy used for utilizing kenaf fibre into automotive component was provided from the Eco-environ website for automotive industry, which was used by Lee and Ofori-Boateng (2013) to assess the environmental sustainability of bioenergy production.

Statistical Analysis

The data obtained by the methods and procedures described in kenaf cultivation, processing into core and fibre and utilize into automotive component and their carbon footprint, carbon dioxide sequestration, and emission, were analyzed using SPSS22 and Excel13, and then converted into figures.

RESULTS AND DISCUSSION

Carbon Footprint of Producing Kenaf Fiber among the Three Cultivated Areas

Figures 1, 2, and 3 illustrate the carbon footprint of kenaf cultivation in Areas A, B, and C, respectively. The investigation showed the environmental importance of conversion of kenaf stem in the nine subareas to bast and core and other waste during the kenaf journey from cultivation to processing and utilization. All three areas provided a similar average carbon footprint. Farm C2 had the highest footprint (1600 tonne CO_2/tonne/year) followed by FarmB1 (1200 tonne CO_2/tonne/year), and finally FarmA2 (1000 tonne CO_2/tonne/year). This data prompts some recommendations for kenaf cultivation for carbon dioxide importance to the environment that will assist in mitigation of the climate change impact and risks; this will be of much value to abate CO_2 locally, nationally, or internationally. The total estimated quantity of carbon footprint of kenaf cultivation in the studied areas, as well as the farms is about 0.750 tonne CO_2/tonne. The environmental benefits derived from kenaf cultivation will contribute positively to reducing the environmental pressure caused by the emission of pollutants into the atmospheric layer. Lam *et al*. (2003) showed that kenaf cultivated in 121 days and biomass of 37 to 75 tonne/ha/year can absorb 66 to 135 tonne CO_2/ha/year (doubled harvested year). Sing *et al.* (2018) showed that the carbon-based sustainability index for jute (2.27) and kenaf (2.07) were highest due to better carbon use efficiency. Sustainability index of flax was negative (-0.67) due to higher carbon emission. Fertilization and fibre processing contributed most to GHG emissions. The research recommended that the cultivation of kenaf and processing to produce fibre utilized into automotive components will greatly contribute to the mitigation of the pollutants resulting from farm inputs to cultivate kenaf, as well as the uses of the decorticator to separate kenaf core from bast. The utilization of kenaf into vehicle parts will lead to environmental sustainability and lessen the emission when recycling the parts produced from kenaf core and bast.

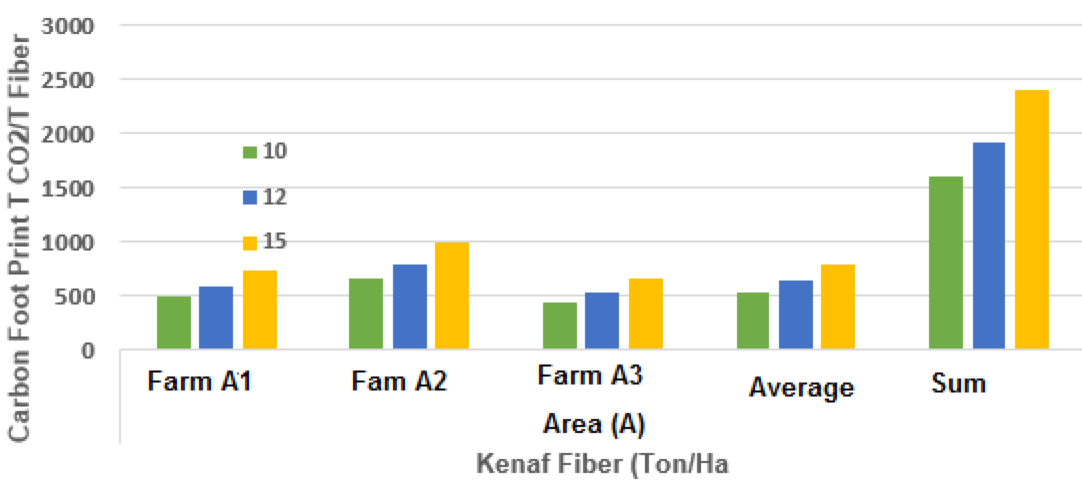

Fig. 1. Carbon footprint of producing kenaf fiber Ton CO_2/t fiber among the three cultivated farms of Area A

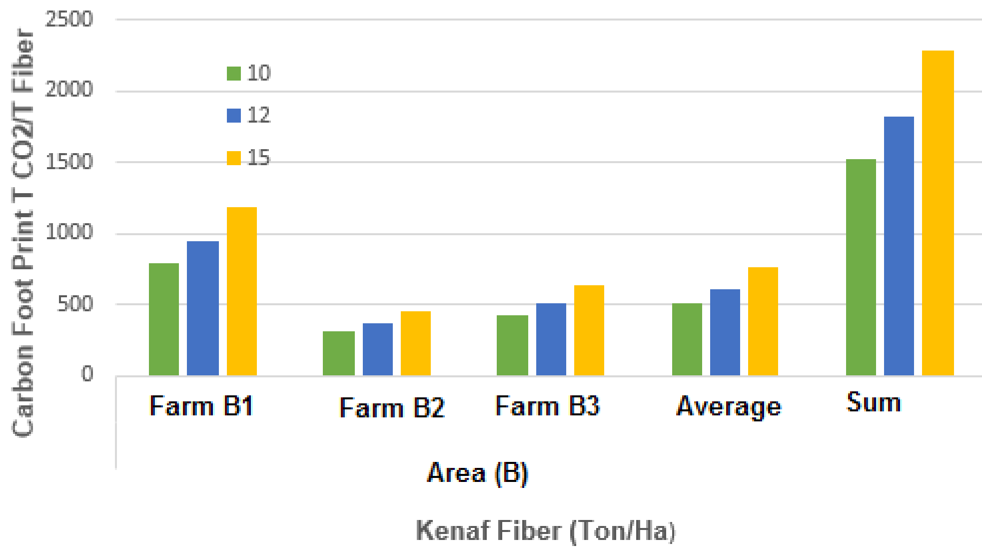

Fig. 2. Carbon footprint of producing kenaf fiber t CO_2/t fiber among the three cultivated farms of Area B

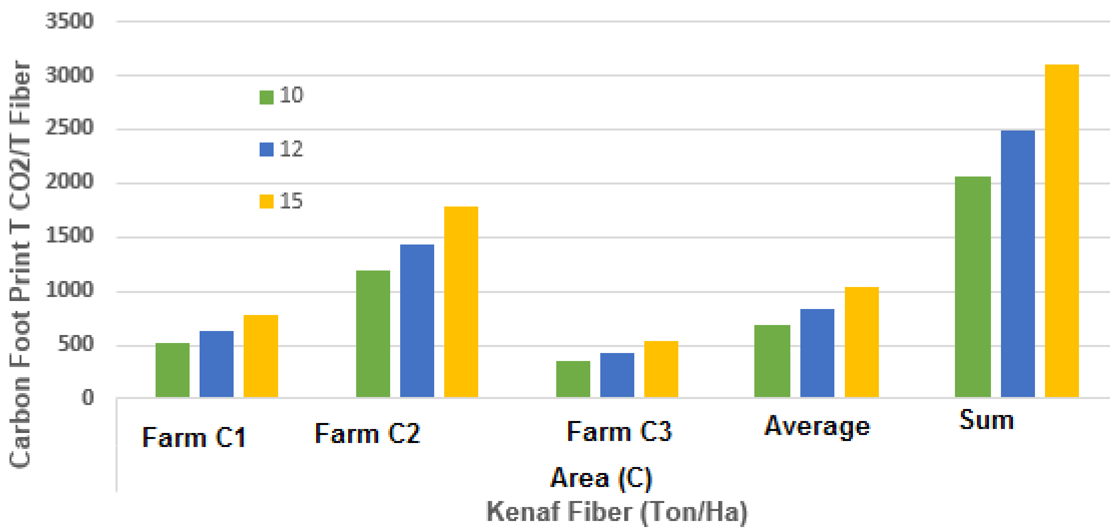

Fig. 3. Carbon footprint of producing kenaf fiber tCO_2/t fiber among the three cultivated farms of Area C

Carbon Dioxide Sequestration and Emission among the States

A comparison of CO_2 sequestration and emission of kenaf cultivation as depicted in Fig. 2 showed that the state of Pahang absorbed the highest amount of CO_2 from the atmospheric layer, followed by Kelantan, Terengganu, and lastly Perak. More so, in terms of district absorption of CO_2 during kenaf cultivation, Pekan in Pahang state had the highest sequestration rate 40000 tonnes/ Ha /year) followed by Besut in Terengganu) (25000 tonnes/Ha/year Pasir Mas in Kelantan to (20000 tonnes/ Ha /year), and lastly Kuala kangsar in Perak state 5000 tonnes/hectare/year). Based on the study results, some recommendations can be made. These include the application of certified emission reduction CER, following the IPCC protocol to claim the sequestrated carbon dioxide by the current cultivated areas. This will be greatly beneficial to the government as well as kenaf agronomists in the use of their cultivated area as abated allowance locally, nationally, or internationally. Also, the total estimated quantity of carbon sequestration of kenaf cultivation in the studied states as well as the district is approximately 180,000 tonne CO_2/tonne/Ha/year. The environmental benefits derived from kenaf cultivation will contribute positively to reducing the environmental pressure caused by the emission of pollutants into the atmospheric layer in Malaysia. Such pollution is as published by the Department of Statistics Malaysia (DOSM 2014). The main pollutants in the country are from industries, motor vehicles, and power plants, which release 101.9, 2092, and 742.9 thousand tonnes of CO_2 per year, respectively. The more cultivated area of kenaf plant will contribute greatly to the alleviation of the above-mentioned pollutants.

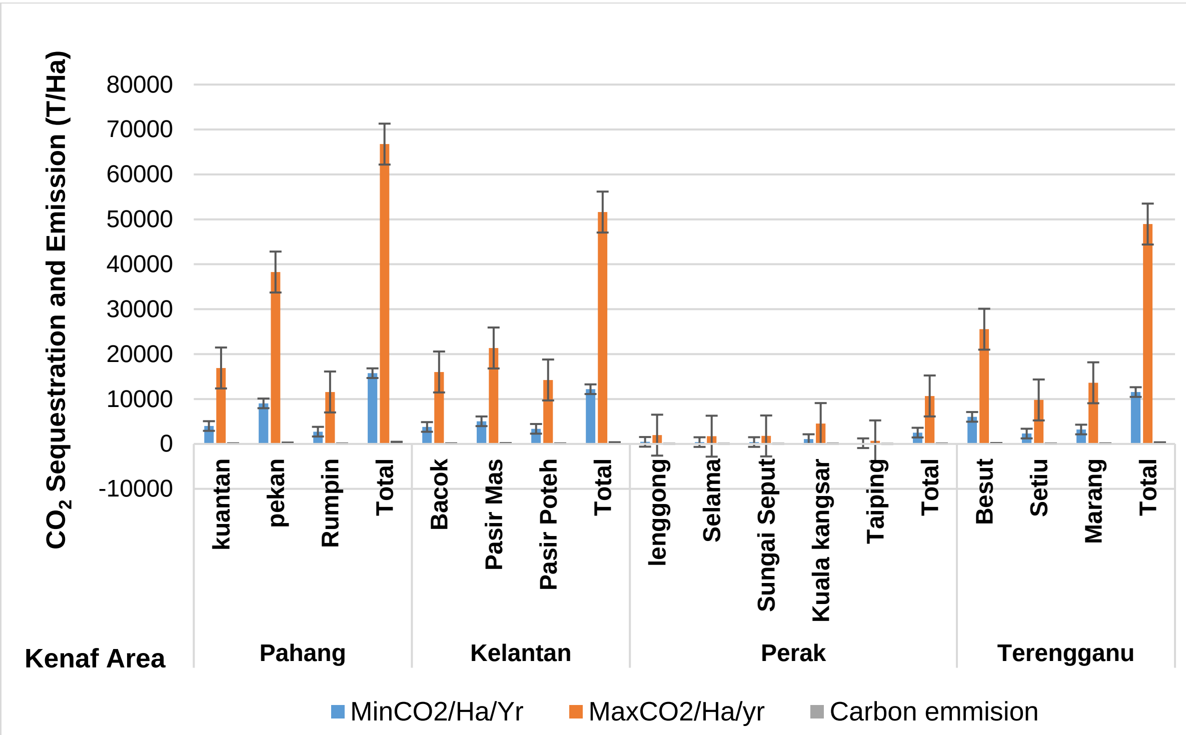

Fig. 4. Comparison of CO_2 sequestration and emission among the states

In the future, more efforts must be taken to evaluate the natural fiber crop products which are produced by the countries and compare them to the other peer countries. The environmental impact of kenaf materials processing in the vehicle components industry might speed up the acceptance of using core and bast parts; therefore improving the potential social and environmental paybacks.

CONCLUSIONS

1. Substituting non degradable materials with renewable materials such kenaf core and bast fibers can be expected to result in the reduction in vehicle weight and abatement of Greenhouse Gases emissions. Using kenaf core and bast parts for automotive components has the potential to alleviate the environmental impacts of the transportation sector achieving the targeted emission reduction and regulations in the future.

2. A sustainability check was carried out as a requirement for the commercial success of kenaf without hurting their environmental performance. The study analyzed CO_2 sequestration as well as CO_2 emissions by the studied areas and estimated the environmental impacts.
3. The outcome of the research implies that the government should set legislation and develop local laws to be implemented for using natural fiber manufacturing products instead of other synthetic products.

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