Indian Journal of Agricultural Sciences **88** (8): 1305–11, August 2018/Article
https://doi.org/10.56093/ijas.v88i8.82579

Carbon footprint and energy use in jute and allied fibre production

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Received: 23 September 2017; Accepted: 15 May 2018

ABSTRACT

The study examines carbon and energy footprints of jute, kenaf, sunnhemp and flax fibre production systems. Energy productivity was lowest in flax fibre production as compared to other fibre crops. Flax fibre production consumed more chemical fertilizer, diesels, pesticides and seed energy in comparison to other fibre crops. The carbon footprints of the all fibres crops did not differ significantly and were in the order of 566, 520, 445 and 423 kg CO_2-eq/tonne of fibre for jute, flax, kenaf and sunnhemp, respectively. 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. Overall, the carbon footprint of bast fibres was 20–50% lower than that of synthetic/artificial fibres.

Key words: Allied bast fibres, Carbon footprint, Energy use pattern, Jute

Natural fibres are produced and used to manufacture a wide range of traditional and novel products from textiles, ropes and nets, brushes, carpets and mats, mattresses to paper and board materials. Globally, jute is the second largest natural fibre produced, with an estimated average production of 3 million tonnes per year (FAOSTAT 2016). The overview of worldwide production (FAO data 1962–2014) shows that jute has always been the most dominant bast fibre crop. India is single largest producer of jute goods in the world, contributing about 60% of the global production and providing employment to 4.85 million farm families, industrial workers and traders. Jute and allied fibres are important raw materials for natural geotextiles. The governments of India, China, Brazil, and South Africa have been extensively promoting the development and use of geotextiles which is further expected to augment the demand over the coming decades. The total global market for geotextiles is expected to reach at least 8.24 billion by 2020 (GVR 2015).

Cultivation and processing of natural plant fibres consumes water, uses synthetic fertilizers and pesticides, and also results in emissions of greenhouse gases (Rana *et al.* 2014). Carbon footprints of natural fibres depend on their cultivation practices and post-harvest processing. Decreasing the amount of energy needed for crop production would be one of the most effective ways to decrease a carbon footprint. This is due to the fact that agriculture is responsible for roughly up to 334.41 million tonnes of CO_2 equivalent, of which 13.76 million tonnes is CH_4 and 0.15 million tonnes is N_2O. About 21% of the emissions were from rice cultivation and crop soils emitted 13% of the total CO_2 equivalent emission (GoI 2010). Based on the above described situation, the objective of this study was the evaluation of the carbon footprint and energy use pattern of the four most important natural bast fibres, viz. jute, kenaf, flax and sunnhemp to provide the industry with reliable data regarding the environmental impact of these fibres, which will help them in choosing the natural fibre with the lowest carbon footprint.

MATERIALS AND METHODS

The study on jute, kenaf and flax was conducted at Research Farm of Central Research Institute for Jute and Allied Fibre (ICAR-CRIJAF). The study area located in Barrackpore of West Bengal (India) at 82° 26′ E, 22° 45′ N and elevations of 9 m. The study on sunnhemp was conducted at Pratapgarh of Uttar Pradesh (India) located at 82° E, 22° N and elevations of 45 m. Climate of both location are humid (rainfall> 1300 mm) with a distinct wet monsoon, summer and a cool winter season. Average maximum and minimum temperatures during the experimental period were 39.9 and 10.2°C, respectively.

This study covers the cultivation, harvest, retting and processing of natural-bast fibres. The system studied seven general processes which include field operations, seeds, fertilization, pesticides, retting, transportation and fibre processing. Machinery for land preparation, sowing, fertilizer-application, herbicide and pesticide-application, irrigation, cutting, turning, swathing, baler and bale-mover

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were considered as field operations activities. Based on a study from Evans *et al.* (2006), the carbon, methane and NOx requirement of seeds is estimated as those for fibre-cultivation, with an allocation to seed of 70%. Road transportation to the cultivation area with a round trip of 100 km and low-density polyethylene (LDPE) packaging weighing 4 kg were also assumed. Fertilization classifies emissions from mineral fertilizer and organic manure. Fertilizers induced N_2O-emissions were taken as 1% of applied N. According to the definition of EPA2, herbicides, insecticides and fungicides and their emissions are included in this system stage. Water retting, a biological fibre separation process, is used with jute, kenaf, flax and sunnhemp. *In vitro*, experiments conducted over four years in jute-retting tanks indicated that about 3.1 mg of methane are evolved per gram of jute stem retted (Banik *et al.* 1993). It was estimated that about 15% of the anaerobically decomposing stem tissue in retting ponds is converted to methane (Mudge and Adger 1994). Based on such scientific estimates, one tonne of stem accounts for 0.018 tonne methane per tonne of stem. Transportation includes carrying of fibre from the field to the fibre processing facility or from the water-retting facility to the 'fibre-fine opening-process'. Fibre processing includes electricity for the machineries and diesel fuel for the fork-lifter at the production site and total fibre opening process.

The labour, machinery power, diesel fuel, chemical fertilizers, chemical pesticides and irrigation were identified as inputs to assess the amount of energy usage while the fibre and stick in form as output. Input requirement and output of each fibre crops is given in Table 1. The amount of each input was multiplied with the energy coefficient equivalent as listed in Table 2 to calculate the energy use per hectare. Farmers commonly use tractors and other agricultural equipments for their land preparation, planting, harvesting and in-field hauling.

Energy equivalents (MJ, mega joule) for all inputs were summed to provide estimates for total energy input. Evaluation of manual energy (E_m) was computed (Umar 2003) as

$$E_m = 1.96\ N_m\ T_m$$

where, N_m, Number of labour spent on a farm activity; T_m, Useful time spent by a labour on a farm activity in hours. The total manual labour was recorded in each operation along with working hours, which was converted to man-hour.

Mechanical energy (E_t) was computed by quantifying the amount of diesel fuel consumed during the tillage, sowing and threshing operation using the formula (Umar 2003) as

$$E_t = 56.31D$$

where, D, amount of diesel consumed (litre). Output energy from fibre product was calculated by multiplying the amount of production and its corresponding energy equivalent.

Energy ratio is the energy return on energy investment (Andrea *et al.* 2014, Tieppo *et al.* 2014). It is an indicator used to determine the productivity and efficiency of energy in the crop production system. It is observed that a little portion of the input energy is utilized in the production process if the ratio is high. While most of the input energy is consumed to maintain the process if the ratio is low (Gagnon *et al.* 2009).

The amounts of GHG emissions from inputs in jute and allied fibre production were calculated by using CO_2, N_2O and CH_4 emissions coefficient of inputs. GHG emission is calculated and represented per unit of the land used in crop

Table 1 Input requirement and output of fibre crops per hectare

Particular	Units	Fibre crops				Data source/ Reference
		Jute	Kenaf	Flax	Sunnhemp	
Inputs						
Labour	h	169	193	148	135	Bhattacharjee *et al.* (2007); Ghorai *et al.* (2010); Gupta *et al.* (2006); Husain *et al.* (2009); Kumar *et al.* (2015); Tripathy *et al.* (2010)
Diesel	L	21	21	21	30	
Tractor	h	6	6	6	6	
Manure	q	50	50	50	50	
Seed	kg	6	15	60	40	
Nitrogen fertilizer	kg	80	60	80	20	
Phosphorus fertilizer	kg	40	30	40	40	
Potassium fertilizer	kg	40	30	40	20	
Insecticide	kg	0.75	1	1	1	
Fungicide	kg	0.75	1	1.5	1	
Herbicide	kg	2	2	0	2	
Irrigation	mm	50	0	150	120	
Output						
Fibre (dry mass)	q	32	20	10.5	12	
Wood stick (dry mass)	q	45	52	2.5	40	

Table 2 Energy equivalent of different inputs and outputs of fibre crops

Particular	Units	Energy equivalent	Data source / Reference
Inputs			
Labour	h	1.96	Mittal and Dhawan (1988); Devsenapathy *et al*. (2009); Demircan *et al*. (2006); Ozkan *et al*. (2004); Acaroglu and Aksoy (2005); Kitani (1999)
Diesel	L	56.3	
Tractor/Farm machinery	h	62.7	
Electricity	KWh	11.9	
Manure	kg	0.30	
Jute Seed	kg	10.5	
Other fibre seed	kg	5.1	
Nitrogen fertilizer	kg	60.6	
Phosphorus fertilizer	kg	11.1	
Potassium fertilizer	kg	6.7	
Insecticides	kg	115	
Fungicides	kg	295	
Herbicide	kg	85	
Irrigation	m^3	1.02	
Output			
Fibre (dry mass)	kg	11.8	
Wood stick (dry mass)	q	18.0	

production, per unit weight of the produced yield and per unit of the energy input or output (Soltani *et al.* 2013). The amount of CO_2 produced was calculated by multiplying the input application rate per hectare (e.g. labour, diesel fuels, chemical fertilizers, herbicides and pesticides) by its corresponding coefficient enumerated in Table 3. The emissions were measured in terms of reference gas, CO_2 (IPCC 1995). Emissions from farm inputs (diesel, nitrogen, phosphate, potash) were converted to kg $CO_{2\text{-eq}}$.

The total emissions of greenhouse gases were determined using the following equation (Kramer *et al.* 1999):

$$\text{GHG emission} = \sum GWP_i \times M_i$$

where, M_i is the mass (in kg) of the emission gas, and GWP_i is the Global warming potential. The GWP of CO_2 is 1 (with a time span of 100 years), CH_4 is 21 and N_2O is 310. The score is expressed in terms of kilogram carbon dioxide equivalent (kg $CO_{2\text{-eq}}$).

There are three main Carbon Footprint standards that

Table 3 Greenhouse gas (GHG) emission coefficient of inputs

Input	Unit	GHG coefficient (kg $CO_{2\text{-eq}}$ /ha)	Data source/ Reference
Mouldboard ploughing	MJ	15.2	Singh *et al*. (1999)
Field cultivation	MJ	4.0	Pathak and Wassmann (2007)
Seed sowing	MJ	3.20	Pathak and Wassmann (2007)
Machinery	MJ	0.071	Dyer and Desjardins (2006)
Diesel fuel	L	2.76	Dyer and Desjardins (2003)
Manure	kg	0.0032	Pathak and Wassmann (2007)
Nitrogen (N) fertilizer	kg	1.30	Lal (2004), Pathak and Wassmann (2007)
Phosphorus (P_2O_5) fertilizer	kg	0.20	Lal (2004), Pathak and Wassmann (2007)
Potassium (K_2O) fertilizer	kg	0.20	Lal (2004), Pathak and Wassmann (2007)
Herbicide	kg	6.30	Lal (2004), Pathak and Wassmann (2007)
Insecticide	kg	5.10	Lal (2004), Pathak and Wassmann (2007)
Fungicide	kg	3.90	Lal (2004), Pathak and Wassmann (2007)
Water for irrigation	mm	0.05	Pathak and Wassmann (2007)
Harvesting	MJ	10	Pathak and Wassmann (2007)
Retting	tonne	434	Banik *et al*. (1993)

Table 4 Typical values of compositions and stored carbon dioxide in jute and allied fibres

Organic material	Cellulose (kg/kg fibre)	Hemicellulose (kg/kg fibre)	Lignin (kg/kg fibre)	Stored CO_2 (kg CO_2/kg fibre)
Jute	0.57	0.13	0.14	1.33
Kenaf	0.55	0.14	0.12	1.27
Flax	0.72	0.18	0.03	1.39
Sunnhemp	0.56	0.08	0.11	0.75

Source: https://www.ecn.nl/phyllis2/Browse/Standard/ECN-Phyllis

are applied worldwide, i.e. PAS 2050, GHG Protocol and ISO 14067. The characterization factors are based on the default values given by the IPCC 2013 (CO_2: 1, N_2O: 265, CH_4: 28; in kg CO_2-eq; timeframe 100 years) (Stocker *et al.* 2013). Stored carbon dioxide was used for the calculation of the carbon footprint for each fibre crop separately (Table 4). As per ISO 14040, mass-based allocation was used for all four fibre crops, as it is more stable than economic allocation, which fluctuates more according to supply and demand depending on time reference, region and fibre type. Inventory data on the fibre crop production were taken from various research work databases of ICAR-CRIJAF.

The carbon based sustainability index (Cs) was calculated (Lal 2004) as,

$$Cs = (Co – Ci) / Ci$$

where, Cs is sustainability index, Co is carbon output (kg $CO_{2\text{-eq}}$/ha), and Ci is carbon input (kg $CO_{2\text{-eq}}$/ha). The total GWP (in kg $CO_{2\text{-eq}}$) were integrated which determined the GWPs per hectare of fibre production.

RESULTS AND DISCUSSION

Energy use in fibre production

The energy consumption calculation for different fibre crops showed that total energy consumption was least in sunnhemp and maximum in flax fibre production due to higher application of farm inputs. As shown in Table 5, significantly higher amount of chemical fertilizer, diesels, pesticides and seed energy were used in flax fibre production compared to other fibre crops. Fertilizer (NPK) is mostly applied with sowing of crops as basal dose followed by 2-3 top dressing of nitrogen fertilizer. Flax, jute and kenaf used high amount of energy through fertilizer. Pesticide uses were significantly higher in kenaf and flax fibre crops as compared to jute and sunnhemp. Very small difference in energy consumption was observed in field operations (sowing, weeding, harvesting, etc.) for the all four fibre crops.

Table 6 shows the values of energy indices and the distribution of energy input according to the energy forms of different bast fibre crop production. The energy ratio, energy productivity, specific energy and net energy average value were maximum for jute, followed by mesta or kenaf and sunnhemp. The minimum value obtained was in flax fibre crop. The lower value of energy ratio in flax in this study region may explained by comparatively lower yield of flax and lower energy use management. Energy ratio (energy use efficiency) can be increased either by decreasing total energy input or by increasing the total energy output or through application of both specified actions at the same time

Table 5 Energy consumption in jute and allied fibre crops

Crop	Energy consumption (MJ/ha)					
	Field operation	Diesel	Seeds	Manure and fertilizer	Pesticide and herbicide	Total
Jute	2391^{b}	3800^{b}	63^{d}	4170^{b}	480^{c}	10904
Kenaf	2409^{a}	3097^{c}	157^{c}	3948^{c}	1200^{a}	10811
Flax	2267^{c}	5490^{a}	1530^{a}	5204^{a}	1140^{b}	15631
Sunnhemp	1836^{d}	3800^{b}	420^{b}	1790^{d}	480^{c}	8326
CD (P=0.05)	16.23	16.67	10.15	21.71	13.11	
SE±	7.37	7.58	4.61	9.86	5.95	

Mean value in a column followed by a common letter are not significantly different at 5% level

Table 6 Energy indices in jute and allied fibre production

Crop	Energy input (MJ/ha)	Energy output (MJ/ha)	Energy ratio	Energy productivity (kg/MJ)	Specific energy (MJ/kg)	Net energy (MJ/ha)
Jute	10904^{b}	37760^{a}	3.46^{a}	10.89^{a}	0.092^{c}	26856
Kenaf	10811^{c}	23600^{b}	2.18^{b}	10.84^{a}	0.092^{c}	12789
Flax	15631^{a}	12390^{d}	0.79^{d}	1.08^{c}	0.92^{a}	-3241
Sunnhemp	8326^{d}	14160^{c}	1.70^{c}	10.35^{b}	0.097^{b}	5834
CD (P=0.05)	10.54	38.14	0.13	0.07	0.02	
SE±	4.79	17.33	0.06	0.03	0.01	

Mean value in a column followed by a common letter are not significantly different at 5% level

Table 7 GHG coefficient of jute and allied fibre crops

Particular	GHG coefficient (kg $CO_{2\text{-eq}}$/tonne) of fibre			
	Jute	Kenaf	Flax	Sunnhemp
Field operation	58.38	58.38	58.38	83.22
Seeds sowing	19.2	48	192	128
Manure	16	16	16	16
Fertilizer	120	90	120	38
Pesticide	6.75	9.0	10.86	9.1
Herbicide	12.6	12.6	0	12.6
Irrigation	2.5	0	7.5	6
Transport (Field to processing)	11	11	10	10
Fibre processing	320	200	105	120
Total	566	445	520	423

(Ghahderijani *et al.* 2004). In jute, kenaf and sunnhemp, the consumption of inputs is less which in turn leads to more energy ratio value (energy use efficiency) in those crops.

Carbon footprint of jute and allied fibres

Important sources of emissions can be identified through carbon footprint analyses and areas of emission reductions can thus be prioritized (*Carbon Trust 2007).* Carbon footprint calculation in crop production is done by estimation of GHGs emitted at each identified step of the farming. Carbon footprints of jute and allied fibre crops had been calculated and are presented in Table 7.

Jute and Kenaf: The life cycle of jute and kenaf fibre crop starts with its cultivation in field followed by its harvesting and water retting in pond. After retting the fibres are manually extracted from the stems, washed and dried. Lastly, the sun-dried fibres are delivered as rough fibre bundles to the jute mills where the fibres are refined and cut into the desired length for selling to the non-woven producer. The carbon footprint of the jute and kenaf fibre scenario had been estimated as was 566 and 445 kg $CO_{2\text{-eq}}$/tonne of jute and kenaf, respectively. Table 7 shows that fertilization and fibre processing contributes most to GHG emissions.

Flax and Sunnhemp: Cultivation and harvest of flax and sunnhemp consists of ploughing and harrowing, fertilizer application, sowing, pesticide application, cutting the plants, turning, swathing, baling and bale moving. Fibre is processed in a total fibre line, followed by lorry transport of the fibres to the gate of the non-woven producer. The carbon footprint of flax fibre production was about 520 kg $CO_{2\text{-eq}}$/tonne of flax fibre. The impact of seed sowing was found to be highest, followed by fertilizer (Table 7). Emissions from fibre processing rank third in releasing the various greenhouse gases. In case of carbon footprint of sunnhemp fibre, the different stages of cultivation and processing contribute to about 423 kg $CO_{2\text{-eq}}$ per tonne of sunnhemp fibre. Seed sowing, field operation and fibre processing were identified as the major contributing factors of greenhouse gas emissions in these crops.

The results indicated that the emissions related to the fertilizer subsystem are the most important contributors to greenhouse gas emissions (Tongwane *et al.* 2016, Barth and Carus 2015) in each bast fibres (Fig 1). Pesticides, on the other hand, have relatively lesser contribution to the carbon footprint in these crops. Field operations, seed sowing and fibre processing differ for all fibre crops. Field operations and seed sowing in flax and sunnhemp usually cause relatively higher emissions. During processing of these fibres, the emissions are mainly caused by the energy consumption for decortication and fibre opening. The impact of fibre processing in jute and kenaf was found maximum compared to sunnhemp and flax. For sunnhemp cultivation, the emissions from field operations are quite high in comparison with that of other fibre crops. This is due to the lower straw and fibre yield per area unit of sunnhemp. Additionally, emissions from flax seed production are comparatively higher, due to a higher seed rate. Since jute has a very low seed rate, emissions from jute plants are lower compared to the other bast fibre crops.

In the impact category of greenhouse gas emission, natural fibres show lower emissions than fossil based materials. Manufacturing of one tonne of synthetic fibre products, on an average, has an impact of 1.7 tonnes $CO_{2\text{-eq}}$ (PwC 2012). On the other hand, emission of GHG in use of natural fibre crops (from cultivation to fibre factory gate) usually ranges between 0.5–0.7 tonne of $CO_{2\text{-eq}}$ per tonne of natural fibre. Impact of artificial fibre production to climate change is three times higher than the impact from natural fibre production (Jan 2008). Primary energy for producing artificial fibre accounts to 35 GJ/tonnes of fibre, which is seven times higher than primary energy of bast fibre uses (Haufe and Carus 2011).

Sustainability of production systems

In the context of anthropogenic emissions of GHGs into the atmosphere, sustainability of a system can be assessed

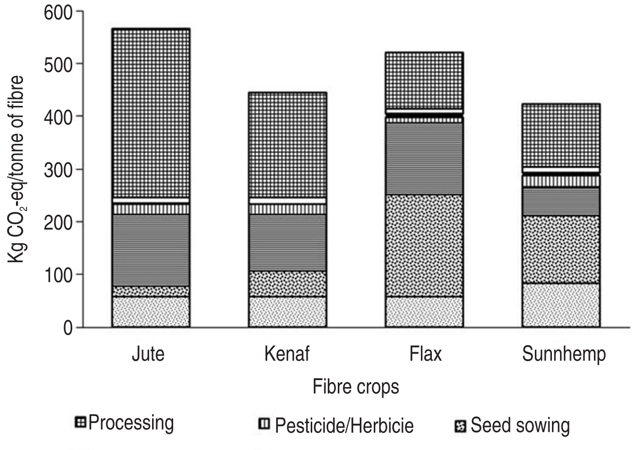

Fig 1 Comparison of the greenhouse gas emission per tonne of bast fibres

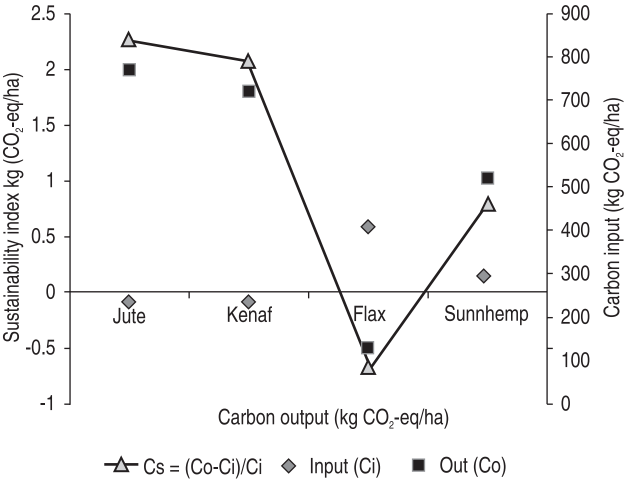

Fig 2 Carbon based sustainability index (Cs) in fibre crops.

by evaluating the temporal changes in the output/input ratios of carbon (C) using a holistic approach (Lal 2004). The carbon based sustainability index for jute (2.27) and kenaf (2.07) were found highest while sunnhemp recorded the lowest value (0.78). In case of flax, the sustainability index (-0.67) was found negative (Fig 2). Thus, C use efficiency is higher in jute and kenaf. In contrast to jute and kenaf, C emission for sunnhemp and flax was high due to higher energy equivalent with respect to their seed rate.

It may be concluded that fertilizer is the major energy input among all the energy inputs in cultivation of jute, kenaf, sunnhemp and flax fibre crops. Energy productivity was lowest in flax fibre production due to low energy output and high fertilizer and seed energy consumption. Kenaf and sunnhemp showed less emission during cultivation and harvesting. As fertilizers recorded a major share in the total calculation of emissions, substituting mineral fertilizers by organic fertilizers may further lower the carbon footprint in these crops. The carbon based sustainability index for jute and kenaf was highest due to better carbon use efficiency. The carbon footprint of these bast fibres is much lower than their synthetic counterparts. Bast fibre composites have 20-50% lower carbon footprint compared to artificial composites.

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