The Environmental Impact of Fibre Crops in Industrial Applications

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1 Introduction

Transition to a more sustainable bio-based economy, as a political consequence of the Kyoto protocol on global climate change (UN fcc 1997), includes a shift of feedstock for energy and chemical industries from petrochemical to renewable resources. The use of non-food crops as major source for renewable resources, however, requires careful consideration of the environmental impact. Data on emission reduction of greenhouse gasses are to be combined with the projections for the year 2050 on the demand for food, energy, and raw materials. For instance the impact of a growing world population and more even distribution of resources have to be included (Van Dam et al. 2004c, Boeriu et al. 2004). It is a good sign that also industries have by now recognised that the concept of "eco-efficiency" is an important way for businesses to contribute to sustainable development (Lawn 2001).

As a major renewable resource lignocellulosic fibres derived from the structural plant tissues will play an important role in this transition. Fibre crops are -among the technical and non-food agricultural products- the commodities with the longest tradition. For example cellulosic fibres for textile and paper pulp production are still important commercial non-food commodities. The markets for fibre crops such as flax, hemp, jute and sisal have seen substantial erosion since the introduction of synthetic fibres after WO II in textile industries (FAO statistics). However, still a market niche has been maintained and numerous new markets are emerging for fibre crops. Especially, the ecological 'green' image of cellulosic fibres has been the driving argument for innovation and development of products in the past decade, such as fibre reinforced composites in automotive industries, building and construction materials, biodegradable geotextiles and horticultural products. In this paper the assumed environmental benefits for the use of renewable materials is placed in the context of fibre crops use in industrial products.

Most information on the environmental impact of agricultural production is available for energy crops and agro-residues used as fuel. The cost of primary production and supply of biomass is considered with respect to energy consumption for cultivation, harvest and transport and is compared to the net energy yield (Hanegraaf et al. 1998). In the case of fibre crops this is more complicated because downstream processing, product performance and life time cycle need more detailed consideration as we will show in this paper.

2 Report outline

A short literature survey is presented on health and environmental issues in relation to the production and use of fibre crops. Next a short introduction to Life Cycle Analysis (LCA) is given and the various commonly applied methods for quantifying ecological impacts are discussed in short. The available literature on LCA of fibre crops is reviewed and placed in the perspective of the role of renewable resources in sustainable developments and (emerging) market applications for fibre crops. The potential sources of environmental gain during service and end-of-life of cellulosic fibre filled materials compared with other materials is addressed. As an example an analysis of the environmental impact of the production of theoretically optimal flax versus glass reinforced construction beams is presented in an annex (Bos 2004).

3 Health concerns for natural fibre processors

The general perception of people on materials made of fibres like flax, hemp, jute, coir and sisal is that they will be more friendly for employees in the processing industry, giving for instance less skin irritation than glass fibres and that they are substantially less hazardous than asbestos fibres. Still, also natural fibre materials can pose health problems for workers.

The health and pollution aspects of water retting are well known (Remani et al. 1989). Therefore, water retting has been abandoned in most cases and novel methods for fibre extraction have been developed.
In a comparative study on the handling of various types of agricultural materials (Dutkiewicz et al. 2000) it was found that threshing of flax in a barn produces relatively high concentrations of dust and endotoxins in the air. The microbial contamination of flax dust was shown to contain both gram positive and gram negative bacteria and fungi (Buick and Magee 1999), the presence of significant levels of endotoxins was demonstrated by sampling of organic dust in hemp processing plants (Fishwick et al. 2001).
It has long been known that the inhalation of organic vegetable fibres can cause occupational lung disease (byssinosis or cotton worker's lung). Respiratory tract infections are recognised in jute mills as a serious risk for workers (Abdullah 1993). Modern fibre processing companies have diminished these problems by using closed processing systems and adequate exhaust hoods, but in older processing facilities in western Europe also nowadays large amounts of airborne dust can be found. In developing countries open processing is still common practice and not the first priority for investment. This aspect should definitively be taken into account when processing facilities for natural fibre/polymer composites and other industrial applications are set up.

In the production of other fibre crops similar problems with dust formation are encountered. Moreover, the risks for workers loosing their fingers by operating mechanically unsafe decortication machines has the effect that it becomes more and more difficult to get young labourers into the fibre processing industries.

4 Introduction on Life Cycle Assessment (LCA)

Life Cycle assessment (LCA)

Quantitative tools for comparing the environmental impact of processes and products are necessary as criteria for the selection of the most sustainable option. Since as early as the 1980's environmental affection due to products has been subject of systematic analysis. Methods such as life cycle assessment (LCA) of products were developed for comparing and classifying environmental effects. Standard LCA's, as defined by ISO 14040-43, include the ecological implications of the whole life cycle of a product as well as its by-products (Rebitzer et al. 2004). The positive or negative effects of by-product accumulation and use may have a strong influence on the total ecological impact of a product. The essence of LCA methodology is that it makes comparison possible between extremely diverse environmental effects.

LCA focusses on the entire life cycle of a product from raw material acquisition to final product disposal (Heijungs et al. 1992), weighing environmental effects damaging ecosystems or human health. The LCA framework and application areas according ISO 14040 to 14043 are given in Fig 1. Based upon this general scheme a method for LCA called the Eco-indicator method (Pre-consultants 1999) was set up by the Dutch government and industries. The method is structured in five parts:

- Goal definition: fixing the aim and scope of the study as well as defining the function and the functional unit of the studied product.

- Inventory: analysing and listing of the polluting emissions and consumption of resources (and energy) per functional unit, and determining the environmental intervention.
- Classification: grouping of the environmental interventions in a number of environmental classes, and then aggregation within the classes using a table of classification factors. The result of this phase is an environmental profile, listing for each class one numerical value.
- Impact assessment: weighing of the classes among each other to integrate the environmental profile into one environmental impact number.
- Interpretation: analysis of the results and estimation of the uncertainties in the results.

Other methods to asses the environmental impact may differ on details, but they all work along similar lines (Pennington et al. 2004). The Eco-indicator method differs mainly in this that its classification and aggregation of environmental interventions results in a single impact number (Table 1). A normalised environmental effect can be calculated by relating the quantified environmental effect to the total effect of a society to the environmental category affected, over a certain period of time (Heijungs 2001). The significance of each effect is classified by using a weighing factor. In this way an apparent small effect can still have a significant influence. The weighing factors, however, are based upon politics and not on science.

The data collection may be very difficult and insecure. Sometimes producers are eager to provide figures needed as input for the calculations, but if they are not, the quality of the input diminishes rapidly. This has obviously dramatic influence on calculated impacts, and might even lead to wrong conclusions. Also difficulties in defining the system limits, for instance when comparing very different materials or products, could lead to inaccuracy in the data.

Energy and resource input

In many studies not a complete LCA is performed but focus lies mainly on fossil energy input and chemicals consumption. This is basically just a part of the outcome of the inventory phase of an LCA study. These studies do not include the emission of hazardous materials or persistence of products in ecosystems. The consumption of fossil energy is then taken as a simple measure for sustainability.

Ecological Foot print

In the case of biomass utilization, the impact on land use is evident. So, in this context the method to determine the "ecological footprint" (Rees and Wackernagel 1994) (expressed in land area per person) can be a useful tool for assessing the sustainability of different systems. The ecological footprint is expressed as the amount of food, energy, water and other resources needed to feed, house, clothe and maintain our lifestyle (including travel, commodities and services), expressed as the productive land area required to produce this. The six categories of land area are distinguished: arable land, pasture, energy source, forest, sea-area and developed land (build-up land) (Hempel 1998). To fulfil all the human needs, it is estimated that an area of 0.01 à 0.02 km^2 per person is required.

Bio-diversity

The ultimate consequence of depletion of fossil resources is the shift of feedstock for energy and chemical industries from petrochemical to renewable resources. Harvesting renewable resources on a vast and intensive scale for human consumption will affect the selectivity of indigenous organisms competing for food and space and may enhance the risk of the extinction of endangered species. The use of renewable resources for non-food applications only enhances this effect. Management of resources therefore requires careful consideration to guarantee the preservation of bio-diversity (Saphores 2003). Methods for quantifying the effects of a product on biodiversity are presently developed.

Use of LCA

The application of LCA to quantify and evaluate environmental impacts of products or processes is relevant for different stakeholders and actors in the product life cycle. Despite the different interest and perception of governments, NGOs and industries, LCA is an important tool for decision making and reaching consensus of best practice for sustainable development and co-operation. LCA is a tool to enhance the awareness of which components of a product life cycle are contributing to the environmental impact most heavily. Decision support in industries is more and more based upon LCA giving quantitative input for material and technology choices, product and process evaluation, benchmarking and choice of location.

For many governments the policy to establish frameworks and conditions for sustainable development is driven by environmental concern. Based upon results of LCA regulatory legislation is formulated to avoid pollution and promote the more sustainable options. Also the UNEP, UNDP, OESO and other international organisations support and promote the development of tools for sustainable development.

The development and use of LCA methods should not be confused with concern of environmentalists on biodiversity or solutions for ecological problems such as pollution of soil, water and air, erosion or deforestation. LCAs are tools to for comparison of products or services and select the most sustainable way for development.

5 Literature on LCA of Fibre crops

In this chapter a review is presented of information available on LCA of fibre crops in the open literature. After a short introduction of previous FAO instigated discussions on the environmental impact of fibre crops and initial enquiries in the early nineties, the developments since then are discussed. In the first part attention is given to the primary production and processing of fibre crop resources and in the following parts their application and end of life disposal are addressed.

Introduction of environmental issues and FAO Committees on Commodities

At the 24th session of the FAO Committee on Commodity Problems IGG on Hard Fibres and 26th session of the IGG on jute, kenaf and allied fibres, which took place nearly 15 years ago, the environmental implications of the use synthetic materials or natural fibre products were discussed (FAO 1990). The restricted access to scientific research was noted as a difficulty to obtain quantitative results for environmental impacts. A comparative study[1] on the environmental implications of polypropylene (PP), high density polyethylene (HDPE) and polyurethane (PU) as substitutes for natural fibre based products was used as discussion paper for defining the follow-up actions. Their conclusion was that natural fibre production requires less than 10 % of the energy used for production of PP fibres (ca 90 GJ/ton) and ca 15 % when the use of fertiliser was included. Also the impacts of waste production (air and water pollution and solid waste production) were higher for the synthetic products. The water pollution of production processes of natural fibres was recognised to be high, but considered to consist of biodegradable compounds in contrast to the release of persistent chemicals (heavy metals) in the effluent of chemical plants. The waste water treatment for natural fibre production therefore would be technically easier and cheaper. In the production of end-products also a higher energy demand for processing synthetic fibres was indicated, with similar impacts of finishing and dyeing.

Searching the open literature on fibre crops - now more than a decade later - still only limited quantitative information is available on comparative life cycle assessment. This might be due to the restricted information provided by companies. Industries can be reluctant to publish results of their LCA studies for competitive reasons. Another reason might be the relatively small economic importance of fibre crop products for Western industries, resulting in little interest from LCA performing groups.

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[1] by the Environmental Protection Encouragement Agency (EPEA), Hamburg, Germany.

5.1 Primary production of fibre crops and fibre processing

Primary crop production

The only field in which LCA of primary crop production has been elaborated in detail is in the area of energy crops. LCAs were performed for assessing the feasibility for agricultural production of energy crops, yielding e.g. biodiesel, bioethanol or biomass for combustion (Biewinga and Van der Bijl 1996; Hanegraaf et al. 1998; Scholz and Ellerbrock 2002). These studies address the yield of biomass per hectare in relation to the amount of applied fertiliser and the amount of energy used to produce the crop, expressed as oil equivalent per ha per year. For agricultural life cycle assessment the precise definition of an appropriate reference system is of critical importance.

Therefore, the questions to be answered by an LCA, should be precisely formulated (Jungk et al. 2002) and the supposed environmental friendliness of naturally produced materials placed in its context (Moll and Schoot Uiterkamp 1997). For example, the production of ethanol from renewable resources by fermentation compared only on energy efficiency with production through synthesis from fossil carbon sources (Dewulf et al. 2000) indicates that in principle the sustainability of the agricultural production route is better - despite the inputs of energy and agrochemicals. On other aspects of the ecological impact such as eutrophication and acidification the score of bioethanol production and use as fuel may be negative (Fu et al. 2003). In case of isolation of other plant components, higher yields and better energy efficiency and/or by-product and waste utilisation will be required for sustainable production. Addressing all social and economic issues, the exploitation of co- and by-products will be critical for the use of biomass for the production of renewable energy (Venturi and Venturi 2003).

Hemp is one of the crops taken into account in these studies. It follows that hemp is considered to be one of the crops with highest crop productivity and lowest requirement for fertiliser under the climatic conditions of central Europe (Biewinga and Van der Bijl 1996). Despite this, hemp cultivation for energy is concluded not to be suitable due to relatively high transport and raw material costs (Brodersen et al. 2002). Only the residues from fibre production could be utilised as energy source.

Cotton

Most literature on fibre crop LCAs is available on cotton (Kalliala and Nousiainen 1999) as the dominant textile fibre crop. The purpose of these LCAs is either textile ecolabeling or comparison with synthetic fibres. The general conclusion is that the production of cotton consumes less energy than polyester, but demands far more water for irrigation of the crop. The negative effects on the ecosystem of the abundant use of pesticides and fertilisers[2] (eutrophication, nitrate contamination, increase in soil salinity) is in favour of organic cotton cultivation. The impact of transportation on the LCA was concluded to be very low due to bulk shipments.

Criticism on the excessive use of agrochemicals in crops like cotton has led to alternative crop management and eco-labelling of organic cotton. Growing of organic cotton requires R&D on biological pest control (Myers and Stolton 1999). Risk of higher crop losses and higher labour intensity for crop management needs to be accounted for. Another way to approach this problem is the development of transgenic crops with resistance to pests (GMO cotton or genetically modified organisms), which were approved for commercial use in the USA (Zipf and Rajasekaran 2003). Concern on the use and uncontrolled spreading of GMO has alarmed environmentalists to oppose to the use of these crops, despite the positive effect on use of crop protection chemicals. Gene flow to wild varieties is a potential source of ecological hazard and may disturb ecosystems irreversibly.

The cotton processing is largely mechanised, although in some parts of the world cotton is still harvested by hand. Specialised machinery has been developed for the harvesting of seed cotton, which either leaves the plants on the field or returns the trash after stripping. It is important for the

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[2] on US cotton fields over 22.500 tons of pesticides per year (source USDA)

fibre quality that the leaves are removed, so application of chemicals for defoliation is common practice.

On average about 2.5 to 3.0 tons of cotton stalks are generated for every hectare of cotton cultivation. In many developing countries the remaining cotton stalks are used by small farmers as fuel source. On larger farms the stalks are commonly disposed of or burned on the fields to avoid pests. Investigations into the use of cotton stalks as raw material for particle board manufacturing industry are currently being conducted in India (Van Dam 2003).

After harvest, the seed cotton needs to be dried (hot air) and cleaned, and the seeds and remaining trash need to be removed from the fibre by the ginning process, which is performed on a large scale in the cotton processing industries. All these processing steps contribute to the total picture of the life cycle of a fibre product. Detailed analysis and data on input energy and mass balances are not available for those processing steps.

Jute and Kenaf production

Under auspices of the FAO the International consultation on "Jute and the environment" was held in 1993 in the Hague. Many aspects were addressed from jute cultivation and processing to novel technologies for use of jute in disposable packaging, composites and geotextiles (FAO 1993). The importance of the environmental impact assessment for eco-labelling, advertising and product improvement were recognised. A detailed document was presented (IJO 1993) on assessment of the life cycle of jute fabric as compared to competing polypropylene products.

A flow chart of the production chain of jute and kenaf for textile production is given in Fig.2. In addition a general flow chart for other end uses is included. However, the agronomic management and degree of mechanisation of the various cultivation systems may differ strongly per region. For most fibre commodities processing is mechanised to a certain extent.

The average yield of fibre per ha varies between 1.6 and 2.0 tons for jute. Kenaf fibre yield may even reach 2.3 tons/ha. The amounts of nutrient uptake (Nitrogen, N, Phosphorus, P and Potassium, K) need to be compensated for by (inorganic) fertiliser or organic manure supply[3]. For kenaf production moderate fertiliser application is recommended (Webber 1996).

The use of agricultural machinery also adds up to the consumption of fuel and production costs (energy and materials). In the case of jute and kenaf, where the crop is grown many small farmers, the contribution of the primary production to the total ecological impact is very small due to limited use of agrochemicals and machinery. The labour requirement and animal power to work the field is different from site to site and changing drastically when mechanisation is introduced[4].

The first steps of fibre processing are performed on the farm. The bast fibres, comprising 6% of the total dry weight of biomass produced, are extracted by subsequent steps of retting, decortication and cleaning. For each ton of jute fibre 20 tons of biomass residues are produced. Commonly, the residual woody core material or jute sticks are locally applied as source for fuel, and leaves are left on the field to improve soil fertility. Those are not accounted for in the calculation of CO_2 absorption from the atmosphere of jute fibre. The CO_2 absorption per ton dry jute fibre was calculated at 2.4 ton[5].

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[3] The total energy input of the use of inorganic fertilisers is calculated based on energy content of the substance and the amount of energy required for production, transport, storage and application (N 128 mJ/kg; P 26 MJ/kg and K 17 MJ/kg). Similarly, the use of pesticides, e.g. herbicides (467-622 MJ/kg) and insecticides (461-568 MJ/kg) and fungicides (320-476 MJ/kg) is calculated per ha or ton dry fibre.

[4] The total energy input was calculated for jute cultivation based on fertiliser and pesticide input. The manufacture of jute fabric, including the energy required for transport and the addition of (mineral) batching oil in the spinning process, amounts to between 2.3 to 5.7 GJ/ ton product. For the disputed batching oil a broad value of 0.86-3.5 GJ/ton was taken, which is representing the energy content of the amount of mineral oil used. No energy values for the field labour and retting and decortication processes were incorporated. The total energy input thus calculated was 3.75-8.02 GJ/ton fibres.

[5] For the calculation of the CO_2 balance the amount taken up out of the atmosphere by the growing plants is reduced by the amount emitted for the production of fertilisers, pesticides and operation of jute processing machinery. A CO_2 emission factor for transport of 84.3 kg CO_2/GJ energy input was taken, while other emissions were converted using a value of 141.8 kg CO_2/GJ energy input. Resulting

In the retting process micro-organisms (bacteria or fungi) are affecting the plant tissues surrounding the fibre cells and thus liberating the fibres from non-fibre parts. The water retting process of jute (15-18 days) in ditches or ponds is consuming large amounts of water (1:10), and causing pollution of surface waters. Organic degradation products of decomposing plant tissues and accumulation of microbial biomass are not considered toxic, but the process is causing oxygen depletion and foul smell emission. An improved eco-friendly method is developed by controlled green fibre retting or ribon retting (Banik et al. 2003).

As a reference system to jute the production LCA data of polypropylene derived from fossil resource were given, including the additives used as stabiliser, pigment, fire retardant etc[6].

The manpower requirement and water consumption were major inputs of the production of jute. The overall conclusion was that based upon the Life cycle impact (LCI) analysis jute can be classified more environmentally friendly than PP. Also some suggestions for product optimisation were given for more sustainable jute production.

Hemp and Flax

The production and processing of annual bast fibre crops such as flax and hemp follow basically the same flow scheme as given for jute (Fig 2). In the developed countries most of the agricultural processes are mechanised (Fig 3) and use of fertiliser and pesticides is common practice. Relatively, as compared to customary agricultural practice in growing of other crops, fibre crops have a low demand for nitrogen (typically recommended for hemp per ha: 125 kg N, 46 kg P, 172.5 kg K; for flax 30 kg N, 100 kg P and 80 kg K), weed control and pesticide. However, some fungi (especially *Botyris cinera*) may cause damage in fibre hemp to the lower part of crop. Chemical spraying of the tall crop is impractical and is considered economically and ecologically undesirable (De Mayer and Huisman 1995).

Flax growing is more demanding on the soil structure quality and drainage than hemp. To avoid pests and contamination of the crop, low amounts pesticides (parathion) and weed control agents (betazon, sethoxydim) are applied (Riensema et al. 1990). In Europe the agricultural production of flax is mechanised and special equipment is designed for harvesting and deseeding. Dew retting is still common practice in flax, which leaves the crop for some weeks on the field (Fig 4).

In a case study on the LCA of hemp for paper pulp production the energy demand for agricultural production is found to be low (1.2 GJ/ton pulp) as compared to the decortication (6.2 GJ/ton pulp) or the pulping processes (15.2 GJ/ton pulp) (D. Kok 2001; Van Berlo 1993).

Coir

The environmental impact of coconut plantations is small and the use of pesticides is only incidental. Moreover, the use of pesticides and fertilisers in coconut production can only be partially ascribed to coir fibre production, since coir is considered the by-product from coconut cultivation. For higher yields the use of chemical fertiliser is advised (375 kg / ha, NPK). In the traditional production of coir fibre from coconut husks the fibre extraction step is giving the highest negative impact on the environment. After (manually) separating the husk from the nut, the husks are soaked and retted for various periods of time (3-6 months) in ponds or backwaters and lagoons (Fig 5). The microbial fermentation process pollutes the surface waters (Umayorubbhagan et al. 1995; Nandan and Abdul Azis 1995; Abbasi and Nipaney 1993) and releases methane gas, which is contributing (28 times more than CO_2) to the greenhouse effect. The result of the retting process is that the fibres are softened and can be extracted from the surrounding pith much easier. Instalment of controlled biological waste water treatment systems and recycling of process water could avoid

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in a total of 520-1120 kg CO_2 emission per ton of jute, while 2.4 ton CO_2 is fixed from the atmosphere by growing jute. A positive balance of 1.3 - 1.9 ton CO_2 per ton of jute fibre produced is thus calculated.

[6] The amount of (fossil) energy required for PP production was calculated here to be more than ten times higher at 84.3 GJ/ton, while also CO_2 emission (3.7 - 7.5 ton/ ton PP) and waste production (5.5 ton/ ton PP) were very large compared to jute.

much of the pollution. The decortication and extraction process traditionally was done by beating by hand. Nowadays, semi-mechanised defibrators or decorticators are in use and the period of soaking is reduced to several weeks. The energy required to operate the machines adds to the environmental impact but data are not available to our knowledge. The residual pith, however, has been piling up at the decortication plants (Fig 6). For each ton of coir fibre 5 tons of coir dust or pith is produced. Valorisation of this accumulated waste material as horticultural substrate or peat moss substitute is currently implemented.

In the analysis of the production process of biodiesel from coconut oil (Tan et al. 2004) different scenarios for heat and power generation from shell and husk as agricultural residues were taken into account. The reduction of net CO_2 emissions relative to fossil fuel was calculated to lie between 80 and 110%. The extent of the benefits was concluded to depend on the utilisation of coconut shell and husk that are available in sufficient quantities. The low-energy inputs of coconut agricultural production by traditional practices also positively contributes to the low emission values, while its low production efficiency is considered to limit the potential of biodiesel production. The net energy value of lignocellulosic residues is taken at 18MJ/kg.

Sisal and Henequen

In the cultivation phase the production of sisal and henequen is not demanding excessive amounts of agrochemicals. Some 50 to 100 kg potassium is applied as fertiliser and occasionally pesticides (insecticides and herbicides) are needed. The fibre yield per hectare for sisal may range between 0.6 to 1.2 tons per hectare, while the yield for henequen is commonly slightly higher at 1.5 tons per hectare. The most severe impact on the environment is in the fibre extraction process (FAO 1991). In contrast to jute, sisal is largely decorticated by machines. Apart from the energy required for operating the decortication plant (estimated 2 GJ/ton), also the accumulation of (biomass) waste and waste water in the fibre extraction process are matters of concern. The wet decortication processes yield large amounts of waste water (100 m^3/ton fibre), that requires effluent treatment before disposal. In many cases this waste water is polluting surface water and ground water near a processing plant, causing damaging effects on flora and fauna and human health. The fleshy leaves of sisal contain only 3-4 percent fibre. Each ton of fibre yields 25 tons of biomass residues. Feasibility studies on utilisation of sisal waste for the production of biogas, fertiliser, animal feed, paper pulp and flume tow recovery are conducted in East Africa and Brazil (Hurter 2000), primarily to reduce processing costs and improve the economics for fibre production, but also to enhance its ecological sustainability. Utilisation of the residues as source for energy, animal feed and organic soil improver have been reported but still are not common practice (Shamte 2000). The largest market for sisal is found in agricultural twine.

Abaca (manila hemp)

The amount of pesticides and fertiliser used in abaca production in the Philippines is negligible. Occasionally some nitrogen fertilzer is applied in Ecuador. However, sensitivity to diseases may affect the crop production. The fibre yield per hectare is between 0.5 and 1.0 ton. The harvesting is still performed largely by hand. For the fibre extraction process or 'tuxying' a special knife is used to separate the leaf sheaths. For the stripping - next to hand stripping- a mechanised spindle stripper is used. After the stripping the fibres are (sun) dried. The abaca fibre extraction process (tuxying) generates 48 tons of biomass waste to produce 1 ton of fibre. The stripping process of abaca fibre also yields large amounts of biomass waste, which releases methane gas while composting and may cause contamination of the ground waters with organic residues. Abaca fibre finds application in textiles, cordage, ropes and twines and is especially valued for pulp production for use in speciality papers and tea bags.

In the pulping process to produce the valued long fibre abaca pulp, the chemicals required for fibre extraction (usually sodium hydroxide and sodium sulphide) and bleaching (hydrogen peroxide) may cause severe damage to the environment, when no measures are taken for chemical recovery systems. Especially in the small scale pulping facilities improvement of the chemical recovery is required.

The energy required to produce cellulose pulp from abaca fibre is very similar to hemp or flax pulping processes and, except for the prolonged beating process, not exceptionally different from wood chip pulping.

Other fibre crops

Some other fibre crops are produced on relatively small scales such as Ramie, Esparto, Curaua, and Kapok. Ramie is produced for textiles and pulping in China, Brazil, Korea and Philipinnes; Esparto grass for speciality papers in North Africa; Curaua recently is promoted in Brazil for use in paper pulp and composites (Leao et al 1998). These crops show a very similar ecological performance as compared with the crops mentioned above and no additional data are available on their LCA. Kapok fibre production in Indonesia and Thailand for pillows, mattresses, and quilts, is not demanding high energy or water for fibre extraction. Kapok is a seed hair that can easily be obtained by removal of the seeds. Here the light weight and relatively high costs for transportation may be a limiting factor.

5.2 - Fibre crop industrial applications

Fibres are commonly applied in a wide variety of products and in many forms, as filler or reinforcement, as insulation or structural elements (Van Dam 1994), as disposable or durable products varying from:

- yarns and textiles,
- ropes, twines and nets,
- non-woven fabrics, tissues
- paper and board products,
- packaging
- building and construction materials, fibre boards, insulation, geotextiles,
- composites and automotive parts,.

The degree of positive environmental impact of natural fibre based products is partly depending on the substitution potential in industry of the various fibres and the energy requirement of the production process, the product performance and functional life time, including options for waste disposal.

Textiles

In the conversion process of raw fibres into yarns and fabrics, energy is used in the various steps (see Fig. 2) for operating the machinery. Most of the processing steps from combing, drawing, spinning, to weaving are fully mechanised, with the exception of the semi-mechanised processing for spinning and weaving of coir yarns. The dyeing, bleaching and softening steps require input of chemicals and measures for effluent treatment. In industrialised countries strict rules are formulated on the use of dyestuffs and processing chemicals (Van Dam 2002). The use of azo-dyes is banned because of health risks and the use of chlorine dioxide containing bleaching agents is discouraged because of their impact on green house gas emissions. In most industrial dyeing and bleaching procedures those chemicals have been eliminated and were replaced by less toxic components. Despite this, the dyeing and bleaching of textile products are still contributing strongly to the ecological impact of products, but do not differ substantially for cellulosic fibre or the synthetic fibre products.

In textile processing no dramatic differences in environmental impact between cotton and polyester are indicated. However, the use of fossil resources to produce the synthetic polymer substantially contributes to CO_2 emission. The assessment of the Life cycle inventory (LCI) of 100% cotton fabrics as compared to 50% polyester cotton fabrics showed that the functional life time of a blended fabric is better and also the energy required for laundering is in its favour (Kalliala and Nousiainen 1999). In the evaluation of the whole life cycle of a textile product it was stated that the phase of consumer use and maintenance has the largest ecological impact (AFMA 1993). Pollution and energy use due to laundering was by far the largest impact factor for textiles.

Ropes, twines, fishing nets

Price and performance of synthetic fibres has led to severe competition with natural fibre products on the market for ropes and binder twines. In many markets these have eliminated the plant fibre products. However, in some applications the biodegradability will have substantial advantages for the environment. For example in horticulture or shipping and fisheries. Nowadays synthetic fishing nets and hawsers are widely used because of their strength, but their persistence is causing severe damage to wild life. Furthermore, when the nets are washing ashore huge amounts of debris is accumulated at the beaches. In the calculation of the LCA of products such effects are generally not weighed or incorporated in the impacts of fish consumption.

Paper and board

The paper and pulp applications of non-wood fibres in wood-free pulps as compared to wood based products have a negative image. This is mainly because the effluent treatment and chemical recovery systems are not fully integrated in the relatively small scale pulping mills in developing countries as is the case in the large scale wood pulping mills in Scandinavia and Canada. Only 10% of the worlds virgin pulp is made from non-wood pulp, and is largely produced in China from wheat and rice straw, bagasse and bamboo (Hurter 2000). The requirement of energy for harvest, transport, chipping and refining of wood and the amount of chemicals needed to obtain high grade pulps could be advantageous for non-wood when the distance to the pulp mill is small (Van Berlo 1994). Therefore small scale processing units for voluminous fibre crops is essential. However, the high costs for chemical recovery are preventing the downscaling of pulping industries, which makes competition with wood based pulping difficult. Only the niche market of the speciality pulps annual crops can compete because higher prices can be asked. Developments for valorisation of discarded by-products from cellulose production, such as lignin in adhesives, coatings and 'green chemicals', is providing a solution for better sustainable use of renewable resources (Gosselink et al. 2004).

Non-woven

Non-woven fabrics by dry-laid needle punching technology can be produced of most types of natural fibres. Each fibre yields a characteristic fabric, depending of the length and softness of the fibre used. In the conventional needle punching process, on a needle loom, dust formation is a point of concern even with cleaned fibre. Dust minimisation is important also to reduce excessive machine contamination. To enhance the coherence in the non-woven mat, for various applications cross-linking chemicals are used, or the fibres are blended with synthetic fibres, and consolidated and finished by subsequent calendering on hot rollers. Alternatively, a wet laid process can be used. With this technology high pressure water jets are used to entangle the fibres and - similar to paper making processes - the fibres form bonds at contact points upon drying, resulting in a strong web structure.

Non-wovens are applied in various forms and products:

- as tissues and hygienic products
- in filters,
- as sorbents in diapers and disposables,
- in building industries as insulation mats,
- as filling material in mattresses, furniture
- in floor covering and carpets,
- in laminates and composites,
- as horticultural substrate and weed control fleece,
- as geotextiles.

In each application the environmental impact of cellulosic fibre based products requires comparison with competing synthetic or mineral products. Especially in the end application the aspects of functional life time and waste disposal of the non-woven product need to be consistent. For single use disposable tissues and diapers, the persistence of synthetic fibres is in favour for the use of renewable and degradable fibres, provided that the technical performance is the same.

The use of synthetic binders affects the impact of the natural fibre products relatively strongly. Blending with thermoplastic fibres (PP, PVA, etc.) or addition of cross-linking agents is common practice to provide better wet strength. In the case of rubberised coir the energy use accounts for the largest impact (ca 13 MJ/kg, Hoefnagels et al. 1994) and is just somewhat higher than needle felt production. However, Hoefnagels et al. (1994) state that the contribution to human toxic emissions of the rubber vulcanisation process (sulphur and zinc oxide) is substantial but still comparatively low to the production of synthetic polymers such as polypropylene or polyethylene.

Geotextiles

Geotextiles are used as reinforcement for embankments and taluds to avoid erosion in civil engineering constructions. The natural biodegradation of the lignocellulosic fibres can be considered to be an advantage in temporary civil engineering applications. However, the functional life time of a geotextile should be sufficient under the applied conditions and give the required protection against erosion as long as the construction needs to be stabilised (Gosselink et al. 2000; Venkatappa Rao 2002; Rao et al. 1994). In many cases on slopes and waterfronts, natural rooting of plants takes over the reinforcing role of the geotextile (Rickson and Loveday 1998). Biodegradation of the soil stabilising geotextile then is desirable (Hoefnagels et al. 1994). Geosynthetics that need to be removed after a period of time cause a considerable disturbance and is very costly. In general those geosynthetics are resistant to degradation and will remain in the soil for long periods of time.

Horticultural materials

Artificial substrates, synthetic binder twines, plastic clips and plant pots are extensively used in the modern horticultural production in greenhouses and nurseries. For the growers the plastics products and substrates for soilless production (e.g. mineral wool) are forming increasingly a problem of disposal. The mineral wool products are a concern for their effects on human health (Islam et al. 2002). Alternatively, the use of renewable growing media have been investigated and coir pith, the residue from coir fibre production, was introduced as renewable substitute for the disputed peat moss or artificial media. Also other fibrous materials and bark have been considered for conversion to ecologically sound alternatives in potting mixtures and substrates, with promising results. In the production and disposal these alternatives can be assumed to require less energy, but no quantitative data are yet available.

The use of synthetic twines has been the result of too fast loss of strength and degradation of the sisal or jute twine under the moist conditions in a greenhouse. The increasing weight of the crops and the risk of damage due to failure of the twine has been the main reason for using the synthetic products.

Biodegradable plant pots based on plant fibres and different binders are on the market. Competition with the plastic plant pots on price is still very difficult, despite the fact that labour intensive replanting in nurseries will be unnecessary when the pots are biodegradable and roots are able to grow through the walls. The ecological advantage for using biodegradable products is not yet included in the product costs. Recently the UK has marked plant pots as packaging material which implies that an extra tax is put on these products. This has increased the interests of consumers and producers in alternative renewable material based plant pots.

Building materials

Building industries are contributing to a large extent to resource depletion, waste generation and energy consumption, while on the other hand the built environment is vital to economic development (Emmanuel 2004). Promotion of the utilisation of renewable resources as CO_2 neutral building materials can only be considered sustainable when it does not result in faster deforestation. Apart from promotion of the use of FRC certified wood, the use of other renewable building products has received limited attention in the building industries. Fibre crops could play a more prominent role in building and construction applications as fibre board material (Van Dam 2004a,b), insulation materials, and as reinforcement or filler in many different products. In lightweight concrete, bricks and loam building blocks, cellulosic fibres have been known to provide good properties. In the production of substitutes for asbestos cement abaca fibres, were proven specifically suitable. However, the effects on ecological impact for renewable building materials have been poorly documented.

Thermal insulation materials based on natural fibres and cellulose have a good technical performance (Valovirta and Vinha 2002). Also the ecological profile, as compared to the energy requirement for the production of mineral wool insulation or expanded polystyrene, can be assumed to be positive (Hoefnagels et al. 1994). However, in an publication of the stone wool industries those arguments are opposite (Schmidt et al. 2004) and lowest consumption of total energy is claimed for mineral wool insulation products.

Application of fibre crops in fibre boards for building has to compete with wood fibres. Substitution is only feasible when the fibres can be produced cheaper than wood chips. In most cases the amount of (synthetic) glue or resin, required for binding the fibres to form strong board materials, is higher in the case of non-wood fibres. This will have a negative impact on the economics of the board product and also on the ecological performance of the product. Coatings, paints and adhesives are necessary to increase the durablity of renewable building products. Presently, these are mainly based on petrochemical products. To increase the environmental performance of renewable building materials, varnishes, paints and coatings based on plant oils should preferentially be applied. Similarly, natural resins derived from plants (e.g. lignin, furans) should be developed for production on commercial scale and become available as binders for boards and as components in protective coatings.

Composites

The LCA of hemp and flax fibre reinforced synthetic polymer composites for automotive parts has been reviewed by several researchers (Bos 2004; Wötzel and Flake 2001; Patel et al. 2003). Comparison for automotive applications with glass fibre reinforced composite products were addressed also by manufacturing companies. Critical evaluation of the product flow from the primary production of the fibre crop to the end of the life cycle of a passenger car reveals that, within the system boundaries, the agricultural cultivation of fibre crops is insignificantly contributing to the ecological impact. The (non-renewable) energy requirements for the production of fibre glass or flax fibre mats (Diener and Sieher 1999) differ substantially (54.7 MJ/kg vs 9.6 MJ/kg). However, relative to the impact of the polymer matrix material, the overall improvements in the use of natural fibres were small.

Apart from the direct benefit of lower environmental impact of the constructive part which is in some cases reached, also during use a composite reinforced with agrofibres could contribute to a lower environmental impact, especially when the part is used in transport applications. Due to the lower weight, fuel consumption of a transporting vehicle could be lowered when any glass fibre reinforced part is replaced by an agrofibre reinforced part[7], as long as the part is designed for stiffness (see appendix). If natural fibre composites are produced with higher fibre content for equivalent performance the amount of synthetic polymer can be reduced as well (Joshi et al. 2004)

A hemp reinforced car part was compared with one from ABS (Acrylonitril Butadiene Styrene copolymer) using several methods, including the Eco-indicator 95 method (Wötzel et al. 1999). It was found that not only there is a minor environmental advantage of the hemp reinforced part during the production phase (only 8%), but also the weight saving due to the application of the hemp reinforced part leads to a (limited) energy saving and thereby further environmental advantage during the use phase.

The life cycle assessment of china reed (*Miscanthus sinensis*) fibre reinforced PP was studied as a replacement for glass fibre reinforced PP for the production of transport pallets (Corbière-Nicollier et al. 1999). Various methods were used to estimate the environmental impact including the Eco-indicator 95 method. They report an environmental advantage of about 30% due to the use of the natural fibre reinforced material. The effect of a 20% recycling level of glass fibre pallets on all impact categories of the LCA was indicated to be insufficient to compensate for the lower impact of the natural fibre pallet. A significant reduction of energy consumption due to weight saving during the use phase was reported. Corbière-Nicollier et al. also show an interesting table of

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[7] The coefficient of reduction of fuel consumption for a gasoline driven car ranges from 0.34 l/(100kg*100km) (for lighter cars) to 0.48 l/(100kg*100km) (for heavier cars), (Eberle and Franze, 1998), whereas the saving on diesel is somewhat lower, ranging from 0.29 to 0.33 l/(100kg*100km).

potential energy saving by various applications of china reed: substitution of a glass fibre transport pallet leads, for a total transport distance of 100 000 km, to a potential energy saving of 2500 GJ/ha, whereas using china reed for heat production as replacement for oil would result only in an energy saving of 200-240 GJ/ha. A higher environmental gain is thus reached by applying the fibre in the transport pallets. This is confirmed by another study, which states that in terms of savings of energy and green house gas emissions application of natural fibres in composites score better than energy crop production (Dornburg et al. 2004).

The effects of the substitution of glass fibre by natural fibres on lower wear of machinery and the health of the workers (sharp edges, dust particles) is not incorporated in the studies so far.
Agrofibre reinforced composites are used now by a number of automotive producers for instance inner door liners, and the amount of fibres used in these applications has increased significantly over the last 8 years (Karus and Kaup 2002).

5.3 End-of-life phase

Possibilities for recycling and reuse prolong the real life time of a compound and consequently reduce its overall impact substantially. The possibilities of energy recovery after the service life of a product will reduce the net energy requirements and will influence the balance of the energy requirement in the production phase.

In contrast to synthetic materials natural fibres can be degraded by micro-organisms and composted. In this way or by incineration the fixed CO_2 in the fibre crop will be released and the cycle will be closed.

For the cases where an agrofibre replaces a glass fibre, a potential advantage can be found in the end-of-life phase. Similar to glass fibre reinforced materials it is impossible to produce materials from agrofibre filled plastics with little reduction in properties by recompounding them after the use phase. In fact, agrofibres generally suffer even more from a renewed heat step than glass fibres (Bos 2004). However incineration can be a desirable option. In this respect, the main advantage of the application of agrofibres fibres can be found in thermosets, which can not be recycled otherwise when reinforced with glass fibre and filled with cheap mineral fillers, or in recycled thermoplastics, which are closer to their end-of-life incineration than virgin thermoplastics. A comparison between various end-of-life scenario's indicated that incineration was probably the most viable option (Bos 2004). The bonus for incineration (which can be substracted from the eco-indicator) is depending on the amount of combustible material in the final product. The reported net bonus for the incineration of PP is 21.5 MJ/kg for a natural fibre (china reed in this case) is 8.3 MJ/kg (Corbière-Nicollier et al. 1999). Glass fibres cost energy (1.7 MJ/kg), during incineration and add negatively to the total Eco-indicator. For the agrofibre reinforced composite part this means that about 25% of the energy costs of the production of the part are won back by incineration. For the glass reinforced part, which costs almost twice as much energy to produce in the first place, circa 13% of the energy costs are won back by incineration.

6 Conclusions

The various systems for assessing the impact of processes and products on the environment and comparison of sustainability of alternatives are diverse and complex, because the weighing factors are of different and incomparable magnitudes and dimensions. Nevertheless, standard protocols and environmental management tools such as LCA have been developed that provide insight in "eco-efficiency" or can discriminate between production systems.

Most literature on life cycle assessment for renewable resources has been elaborated for biomass and energy crop production. For fibre crop production and use in different industrial processes and end markets only restricted data are available.

Considering the whole life cycle of consumer products based on fibre crops, the impact of primary agricultural production phase is only marginal.

The production of fibre crop of various kinds produced in different climatic zones - from cotton to sisal, and from hemp to coir - has divergent impact on the environment in their requirement of agrochemicals for crop protection and mineral supplies. In general, fibre crops other than cotton have a moderate demand for fertiliser and crop protection chemicals.

The environmental impact is also influenced by the energy for operating agricultural machinery for sowing, and harvesting. Large differences between fibre crops can be observed, depending on the degree of mechanisation in the crop production and local traditions. In developing countries manual labour to work the fields and harvest the crop is not uncommon.

Some fibre crops, and especially cotton, require substantial irrigation for obtaining good yields.

In the post-harvest processing steps the fibre extraction process is consuming most (fossil) energy and water, yielding biomass waste and contaminated process water. This forms a considerable risk of pollution of surface waters, when no measures are taken for waste water treatment.

Utilisation of residues and waste for generation of energy or other value added outlets, substantially enhances the overall ecological performance of a crop.

Dust formation may form a source of health risk in dry processing of the fibres, when no preventive measures are taken to protect the workers. Unsafe and obsolete machines that are still in operation in many places can be a cause of accidents in processing industries.

The energy and chemicals requirements for annual fibre pulping processes for production of paper and board and cellulosic fibre products is advantageous. However, chemical recovery for small scale pulping is economically unattractive. Therefore, pulping of fibre crops such as jute, kenaf, abaca and hemp is often cause of severe pollution and integrated waste water control is needed.

Comparison of the production phase of fibre crops with synthetic products or glass fibres, is resulting in that the score of the fibre crops on CO_2 and greenhouse gas emission levels, consumption of fossil energy and resources is much better.

In fibre reinforced composites, blended textiles or non-wovens, the relative impact of synthetic resins and polymers on the LCA is large.

The utilisation phase often contributes the most to the environmental impact of an fibre crop product. For Instance: the wear resistance of a blended cotton fabric is better than a pure cotton product and the energy demand for drying the laundry is lower, therefore, the blended cotton has a better impact over the full life cycle.

The weight reduction of natural fibre composites in automotive applications contributes more in terms of fuel savings than the impact of energy savings in the production phase of the panel.

When the same mechanical strength is desired the advantage of using lignocellulosic fibres over glass fibres in a composite may be lost because heavier constructive elements are required. However, when the same stiffness is required lignocellulosic fibre can give lighter constructive elements, due to their higher specific stiffness.

In the case of building materials the comparison of LCA needs to be made also with the costs of maintenance and replacement in relation to the performance of the material.

The magnitude of the environmental advantage depends obviously on the kind of application. In other words: the environmental gain is usually due to a secondary effect, such as weight saving, and is then not caused by the 'green' origin of the fibre. It is therefore not possible to give a general rule of thumb of the advantages of the use of fibre crop products.

The economic advantage of fibre crops use in many applications is still small as long as the cost of waste management are not included in the product costs. The increasing costs of petrochemical resources will enhance the competitiveness of fibre crops.

APPENDIX 1

Environmental impact of flax fibre reinforced materials versus glass fibre reinforced materials

As an example, a comparative LCA is presented here for different fibre reinforced composite materials with flax fibres or glass fibres. Special focus lies on the mechanical demands of the composite part, dictated by the application, since this proves to be a determining factor as to which material is preferable from an environmental point of view. The work presented in this appendix[8] is based on an LCA, following ISO 14040 and ISO/DIS 14041 (Guinée 2002), the guidelines of CML (Heijungs et al.1992), the Eco-indicator 95 method (Goedkoop 1995) and using the software of SimaPro (Goedkoop and Cleij 1996). The weighing factors used in this method are given in table 1. The data were collected by means of a questionnaire sent to various producing companies and a literature study. The approach to determine the environmental impact of a construction based on its performance -a performance-specific environmental impact- (Bulder et al. 2001) served as basis for this analysis.

The Eco-indicator values for a number of materials, expressed in milliPoints per kilogram material [mPt/kg], are presented in table 2.

Six hypothetical unidirectional (UD) composites are assembled from three matrices, epoxy (EP), unsaturated polyester (UP) and polypropylene (PP), combined with either glass fibres or flax fibres[9]. For these hypothetical composites the properties as a function of fibre fraction is determined. Next, from each of these composites a structural element is designed, either a tie, for a tensile load, or a beam, for a bending load. From the functional requirements -the element should either have a certain strength or a certain stiffness- the dimensions of the element can be determined. And finally from the dimensions of the element the environmental impact can be calculated.

The mechanical properties assumed for this study are shown in table 3. For a UD fibre reinforced composite made from these materials both the modulus, and the tensile strength can be calculated for different fibre volume fractions using a simple rule of mixtures. The modulus and strength of flax and glass fibre composites with the three different matrices, EP resin, UP resin and PP, for three different fibre volume fractions is shown in Fig. 7. It is obvious that the properties are mainly determined by the fibres. Furthermore, from the density and the Eco-indicator of the various material combinations (Fig. 8) it can be concluded that the environmental impact of the composites is determined for the largest part by the matrix and, consequently, that especially at higher fibre volume fractions the flax fibre composites have a lower environmental impact than the glass fibre composites.

Using these material properties, ties of equal load bearing capacity were designed for each material combination, where each tie, with thickness of 100 mm and length 1 m, can carry a tensile load of 1000 kN and taking into account a safety factor of 2. The minimum thickness of the ties of equal strength for each material combination is given in Fig. 9. It is obvious that there is a huge difference in tie thickness between the flax reinforced materials and the glass reinforced materials due to the difference in fibre strength. Converting the fibre volume fraction to weight fraction, and then calculating the Eco-indicator for the fibres and the matrix and adding these values of the various materials, gives the total Eco-indicator of the tie (Fig. 10). It is clear from this graph that for the systems based on EP and UP resins, the environmental impact of the flax fibre reinforced materials is higher than that of the glass fibre reinforced materials. This is due to the lower strength of the flax fibres, resulting in a much thicker constructive element, and consequently the use of more resin. Only for the PP based systems, at higher fibre content some environmental advantage in the use of flax fibres occurs.

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[8] see for details PhD Thesis of H.L. Bos 2004.

[9] The materials are: EP resin (standard resin, mean data of 4 European producers), UP resin (laminating resin, based on data from DSM-BASF Structural Resins, RIVM/LAE, Brydson, Austin and ECN), PP (mean European data), E-glass (production at PPG in Hoogezand, the Netherlands) and flax (hackled long fibres grown in Zeeuws-Vlaanderen in the Netherlands).

The final production step to make the ties is not taken into account in these calculations. Obviously its effect depends mainly upon the temperatures at which the resin is cured, respectively the PP is processed. Generally speaking, the energy consumption of the thicker ties will be higher than that of the thinner ties, so this would only widen the gap between the glass and the flax fibre reinforced materials.

The same calculation can also be performed on ties designed for equal stiffness, where the tie should give a maximum strain of 1 % at an applied load of 1000 kN.
The Eco-indicator of these ties (Fig. 11) shows that the flax fibre reinforced EP and UP ties in this case still show a higher environmental impact. The flax/PP tie shows, depending on the fibre volume fraction, a similar or better environmental impact compared to the glass/PP tie.
The difference in weight between the glass and flax fibre ties is smaller than the difference in thickness, due to the lower density of the flax fibres compared to glass. The Eco-indicator and the mass of this tie plotted versus the fibre weight fraction (Fig. 12) gives a changed situation. For materials with the same weight fractions and thus densities, the flax fibre reinforced materials are preferable from an environmental point of view, and the ties are lighter in weight. This is obviously due to the relatively good specific modulus (modulus per weight) of the flax fibres. The pay-off is that for the glass fibre reinforced materials the tie is loaded up to 19% of the maximum allowable stress, whereas for the flax fibre reinforced materials the tie is loaded up to 33% of the maximum allowable stress.

Apart from stiffness in tension, the bending stiffness is an even more relevant parameter for many constructive parts. For a similar beam put on two simple supports with a span of 1 meter and loaded at the midpoint by a load of 1 kN, which should give a maximum deflection of 10 mm, the Eco-indicator as function of fibre volume fraction is given in Fig. 13. It is clear that for this constructive element the use of flax fibres is preferable from an environmental point of view over the use of glass fibres, except for the flax/EP beam with a fibre volume fraction of 0.2.
The Eco-indicator as a function of fibre weight fraction and the mass of the beam are shown in Fig.14. Obviously, when the materials are compared on the basis of fibre weight fraction, the difference is even larger. Also the flax fibre reinforced beams are lighter in weight than the glass fibre reinforced beams. As long as the loading is relatively moderate, a flax fibre reinforced beam thus is the better choice.

This conclusion is in good agreement with the applications for flax fibre reinforced materials known so far from the automotive industry, where mainly panels are applied that are designed on the basis of a stiffness criterion. Even though these materials are not produced from UD composites but from impregnated fibre mats, the arguments and outcome should be the same. Desired properties coincide in this case with low weight of the constructive part and favourable environmental performance, especially when PP is used as the matrix material.
Comparing the results of this theoretical study on optimal UD composites with similar calculations using experimental material properties, confirms the general results of the study (Bos 2004). Especially for elements designed for equal bending stiffness, the flax fibre reinforced materials are, from an environmental point of view, an interesting alternative for glass fibre filled materials.

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Table 1 Weighing factors used in the Eco-indicator 95 method

Environmental effect	Weighing factor	Criteria	Reference Compound
Greenhouse effect	2.5	0.1°C per 10 years, 5% ecosystem damage	CO_2
Ozone layer depletion	100	Chance on 1 death / year / 1 million people CFK-11	
Acidification	10	5% ecosystem damage	SO_4^{2-}
Eutrophication	5	Rivers and lakes, damage to unknown number of aquatic systems (5%)	PO_4^{3-}
Summer smog	2.5	Occurrence of smog periods, health complaints esp. asthma patients and elderly, occurrence of agricultural damage	CH_4
Winter smog	5	Occurrence of smog periods, health complaints esp. asthma patients and elderly	SO_2
Pesticides	25	5% ecosystem damage	active ingredient
Heavy metals	5	Lead content in blood of children, limited life expectancy and learning performance of unknown number of people	Pb
Heavy metals	5	Cadmium content in rivers, eventually also influencing humans	
Carcinogenics	10	Chance on 1 death per year per 1 million people	

Table 2. Environmental impact of the various materials ▯.

Materials/ Processes	Material	Eco-indicator [mPt/kg]	Remarks
Fibres	Flax	0.34	Hackled long fibres, value might be too low, since production of used pesticides is not taken into account
	Glass	2.31	Including extraction of raw materials, transport and production
Matrix materials	EP resin	10.2	Including extraction of raw materials, transport and production, mean European data
	UP resin	9.45[1]	Value might be too low, because production of energy carriers is not taken into account
	PP	2.99	Including extraction of raw materials, transport and production, mean European data

[1] This value is for hand lay-up, for closed mould processing the eco-indicator would be 3.08 mPt/kg.

Table 3. Tensile strength, Young's modulus and density of the fibres and matrices.

Material	Tensile strength [MPa]	Young's Modulus [GPa]	Density [kg/m^3]
Flax hackled long	750	50	1400
E-glass	2000	76	2560
EP resin	100	3	1200
UP resin	90	2	1100
PP	38	1.4	900

Fig 1. General scheme of Life cycle assessment framework and application areas according to ISO 14040 - 14043.

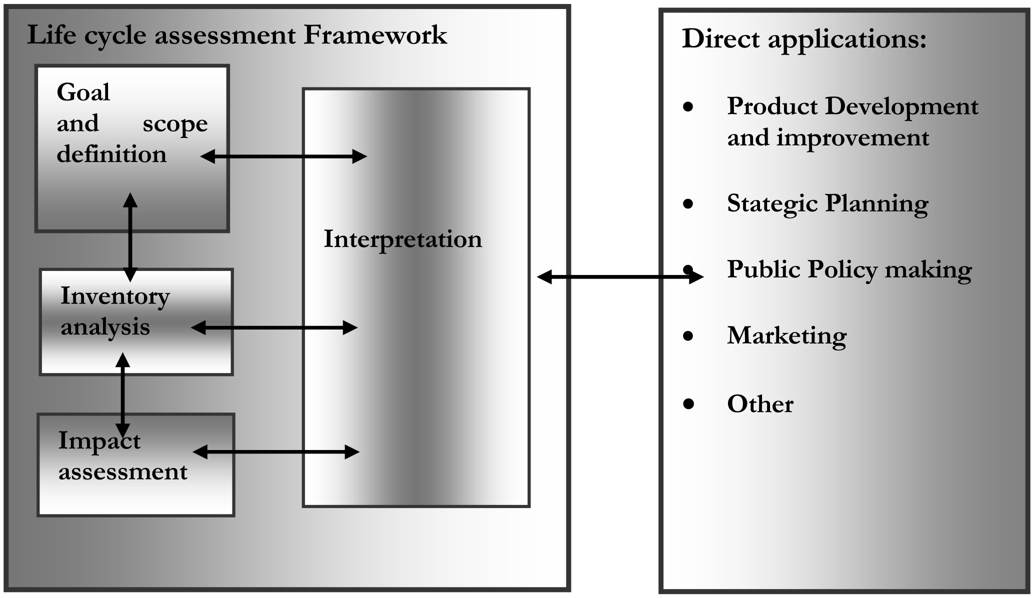


Fig 2. Flow chart of the production chain for fibre crops for textile production and other end uses.

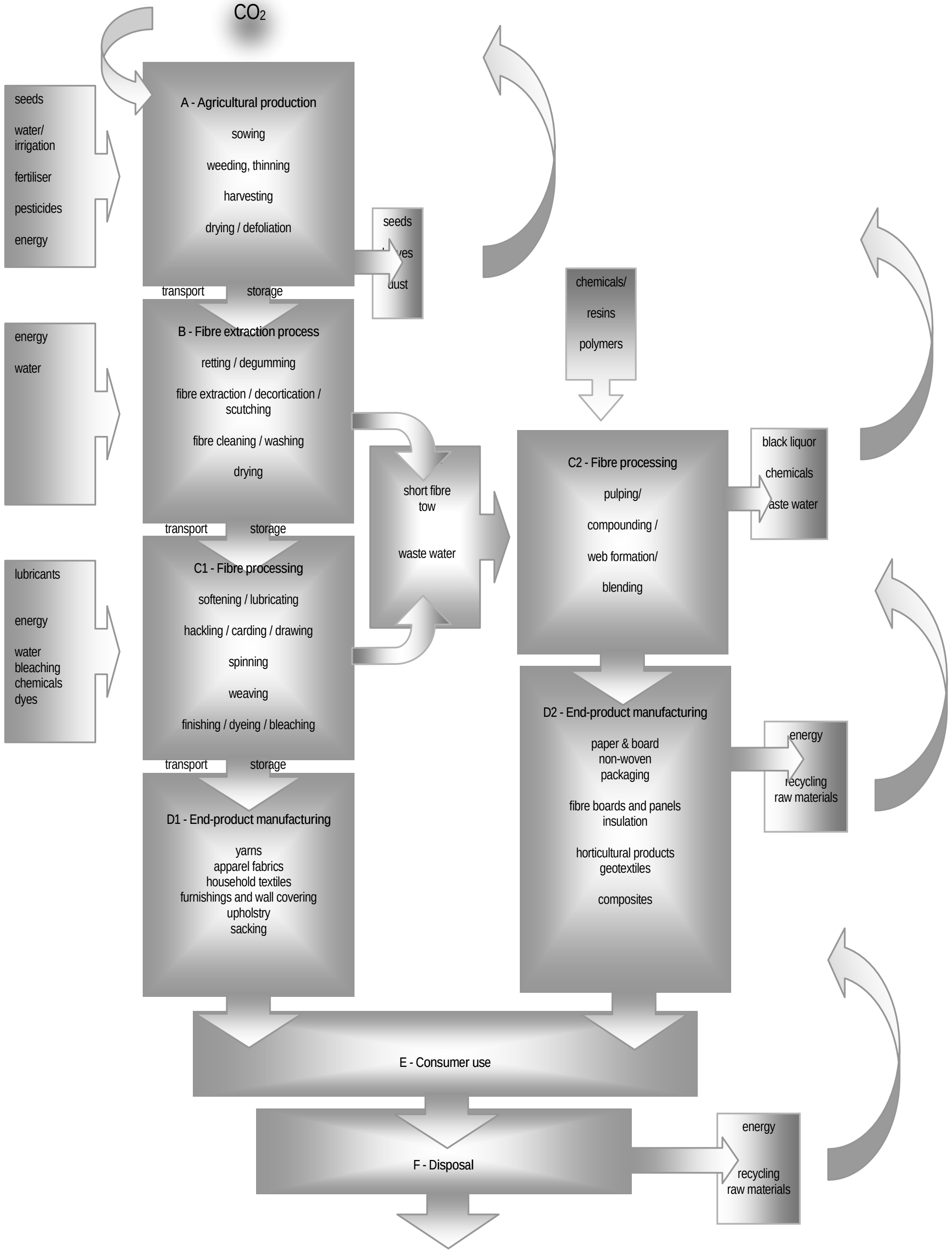


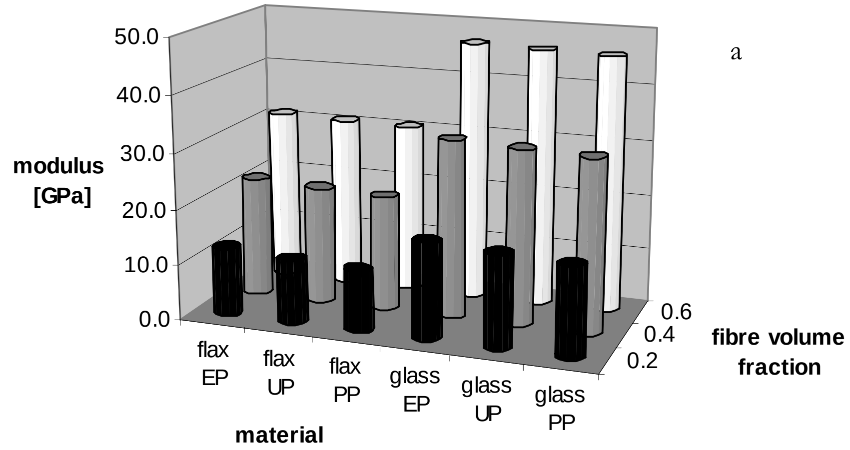
Fig 3. Mechanised harvesting of hemp.

Fig. 4. Dew retting of flax

Fig. 5. Retting of coir husk in the backwaters, Kerala, India

Fig.6. Piling up of coir pith at fibre decortication plant

Figure 7. Properties of the six different composites. (a) Young's modulus. (b) Tensile strength.



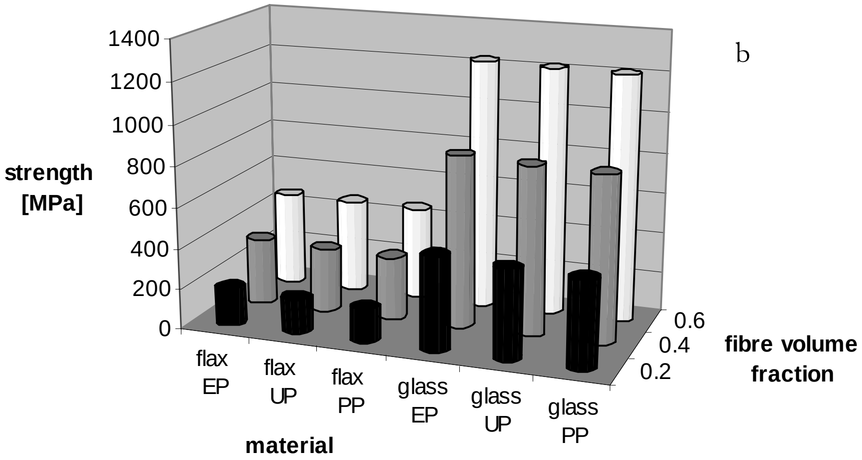
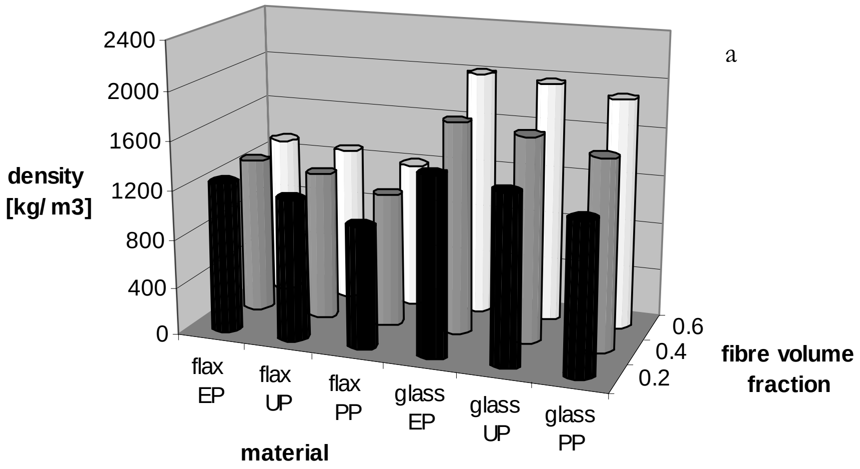


Figure 8. Material properties of the six different composites. (a) Density. (b) Eco-indicator, note that in this graph the order of the volume fractions is reversed for the sake of clarity.



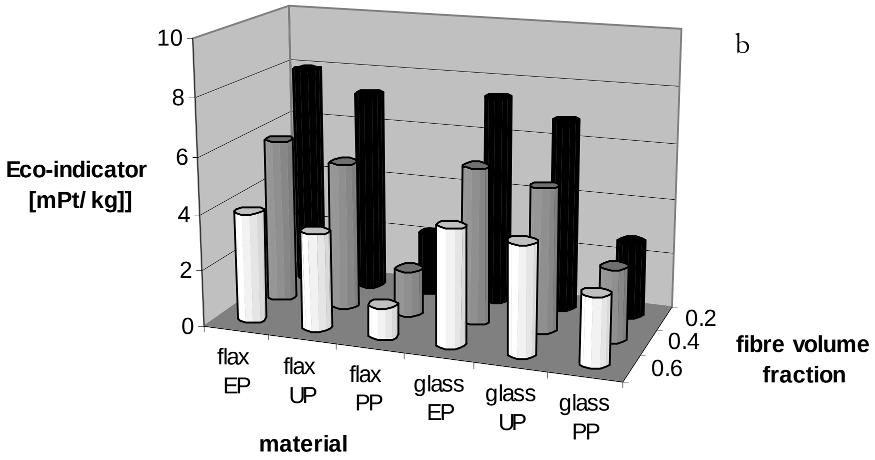


Figure 9. Thickness of a tension tie, width 100 mm and length 1 m, with variable thickness, designed to withstand a load of 1000 kN with a safety factor of 2, as a function of fibre volume fraction, for the six material combinations.

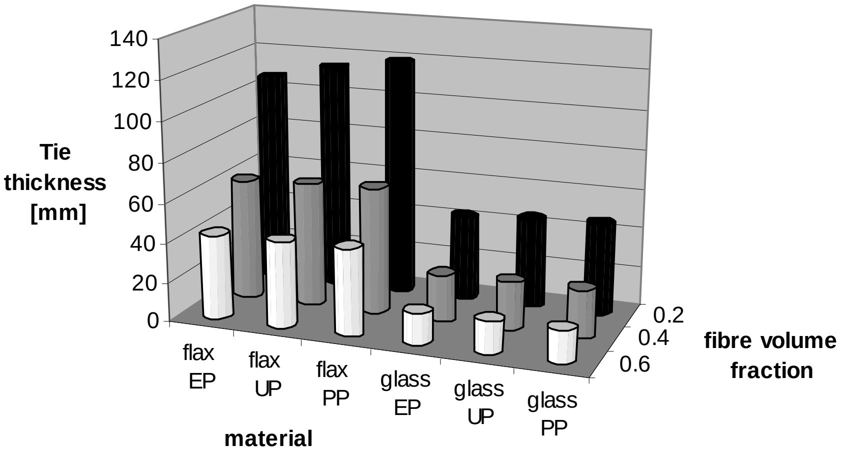


Figure 10. Eco-indicator of a tension tie, width 100 mm and length 1 m, with variable thickness, designed to withstand a load of 1000 kN with a safety factor of 2, as a function of fibre volume fraction, for the six material combinations.

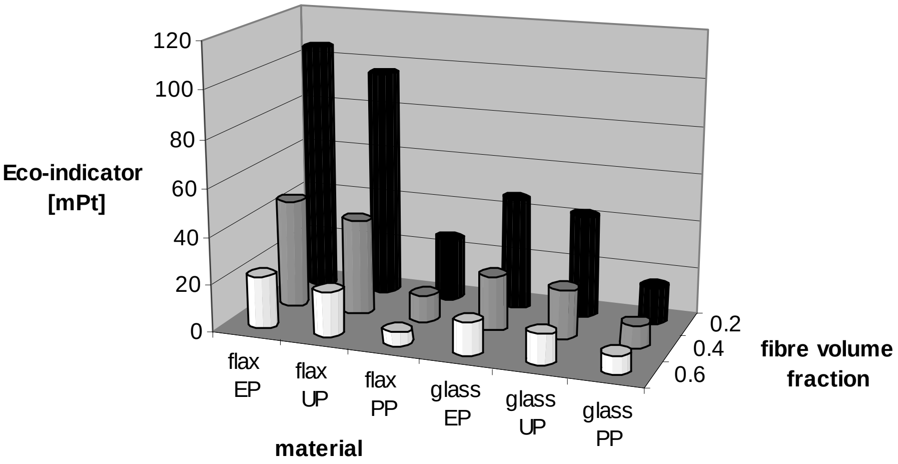


Figure 11. Eco-indicator of a tension tie, width 100 mm and length 1 m, with variable thickness, designed to give a maximum strain of 1 % at a load of 1000 kN, as a function of fibre volume fraction, for the six material combinations.

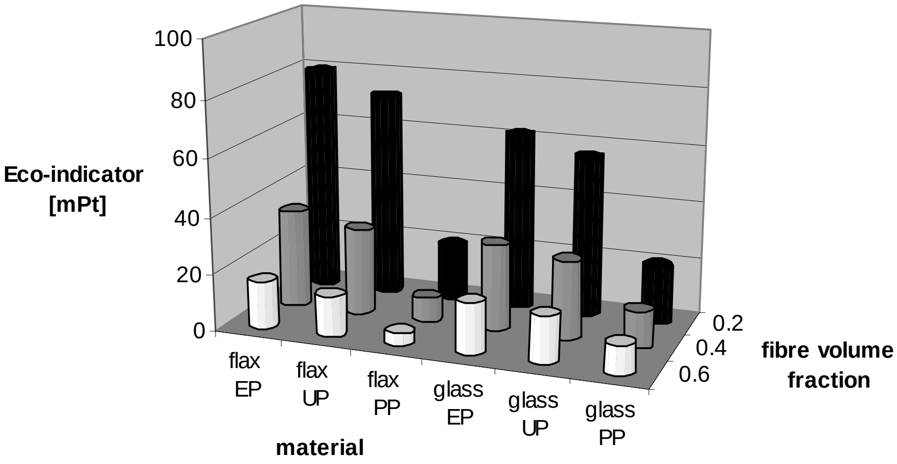
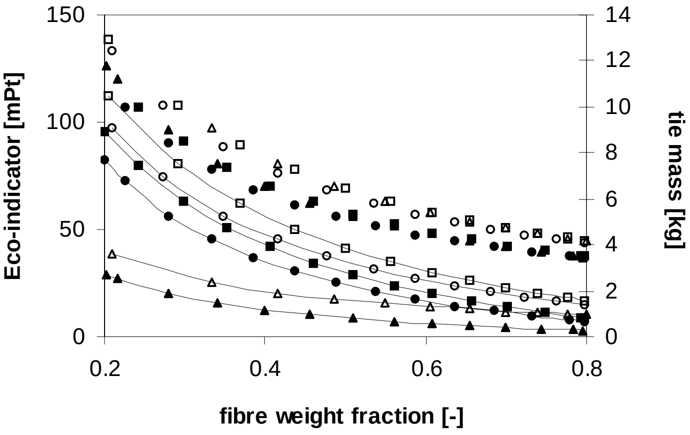


Figure 12. Eco-indicator of a tension tie, width 100 mm and length 1 m, with variable thickness, designed to give a maximum strain of 1 % at a load of 1000 kN, as a function of fibre weight fraction, for the six composites.



■ *flax/EP,* □ *glass/EP,* ▶ *flax/UP,* O *glass/UP,* ▶ *flax/PP,* Δ *glass/PP. The lines in the bottom of the graph give the Eco-indicator, the markers in the top of the graph give the weight of the beams.*

Figure 13. Eco-indicator of a deflection beam, width 100 mm and length 1 m, with variable thickness, designed to give a maximum deflection of 10 mm at a load of 1000 kN, as a function of fibre volume fraction, for the six material combinations.

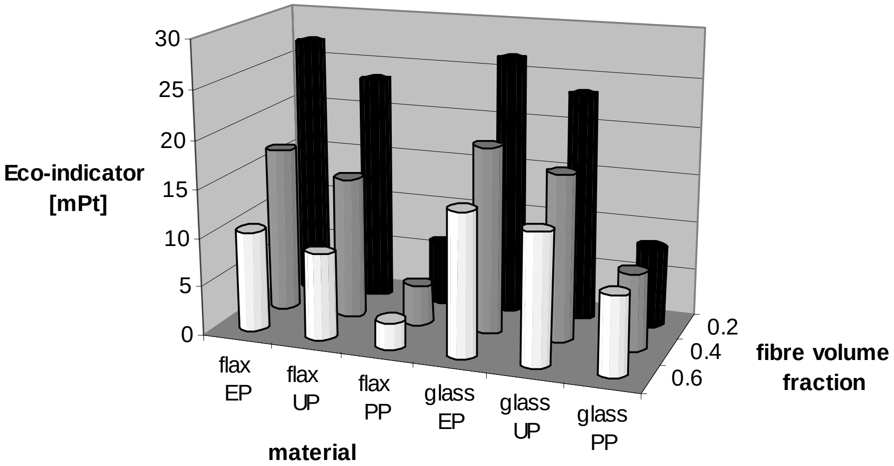
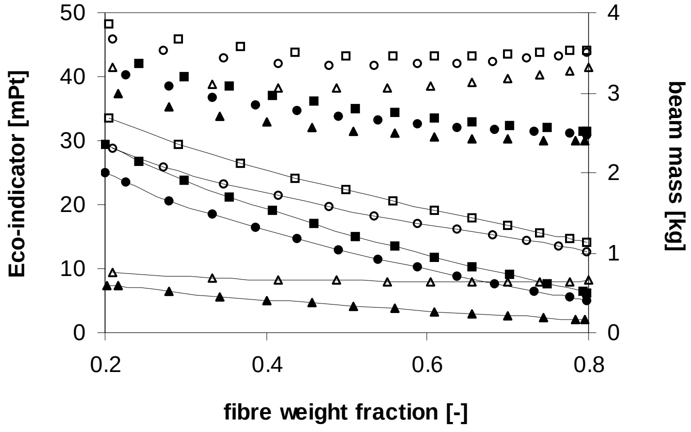


Figure 14. Eco-indicator of a deflection beam, width 100 mm and length 1 m, with variable thickness, designed to give a maximum deflection of 10 mm at a load of 1000 kN, as a function of fibre weight fraction, for the six composites.



■ *flax/EP,* □ *glass/EP,* ► *flax/UP,* O *glass/UP,* ► *flax/PP,* Δ *glass/PP. The lines in the bottom of the graph give the Eco-indicator, the markers in the top of the graph give the weight of the beams.*