FAO of the UN

2012

Unlocking the commercial potential of natural fibres

Market and Policy Analyses of the Non-Basic Food Agricultural Commodities Team

Trade and Markets Division

Food and Agriculture Organization of the United Nations

Contents

[I. Introduction 2](#_Toc350782686)

[II. Factors impacting on market development and the economic significance of sisal 4](#_Toc350782687)

[A. Many favourable factors currently at play 4](#_Toc350782688)

[B. Past market growth below expectations as use of sisal in new applications lags 5](#_Toc350782689)

[C. AN Improved competitive position: Price factors associated with the markets for crude oil and derivatives 7](#_Toc350782690)

[D. AN Improved competitive position associated with environmental concerns 8](#_Toc350782691)

[E. INCREASED RESEARCH ON INDUSTRIAL APPLICATIONS FOR SISAL 9](#_Toc350782692)

[III. The economic significance of sisal 11](#_Toc350782693)

[IV. State-of-the-art research on natural fibres in new applications 14](#_Toc350782694)

[A. INTRODUCTION 14](#_Toc350782695)

[B. Natural fibre composites 16](#_Toc350782696)

[C. TECHNOLOGIES FOR NATURAL FIBRE BASED COMPOSITES 17](#_Toc350782697)

[D. Composition of natural fibres 19](#_Toc350782698)

[E. Principal ADVANTAGES OF NATURAL FIBRE COMPOSITES 22](#_Toc350782699)

[F. composites applications AND cost implications of RELATED TECHNOLOGIES 23](#_Toc350782700)

[G. Fibre Applications: GEOTEXTILES 26](#_Toc350782701)

[H. Biocomposites 29](#_Toc350782702)

[I. Structural Application 31](#_Toc350782703)

[J. Nonstructural Applications 31](#_Toc350782704)

[K. Aerospace Application 34](#_Toc350782705)

[L. Natural Fibre Nanocomposite Applications 34](#_Toc350782706)

# Introduction

Increasingly, the world is realizing that better use must be made of precious natural resources. Environmental awareness has prompted many industries, particularly in high income countries, to consider more sustainable ways of operating. In recent years, much has been said and written about the potential market and commercial benefits to be derived from adapting manufacturing technologies in order to make them more environmentally friendly. While examples of industrial adaptations and of product specifications designed to meet the environmental concerns of consumers are multiplying, there are nevertheless still vast areas where further change is possible, and indeed advisable. However, it is clear that the tide rushing towards environmentally-friendly manufacturing and product output is surging and will continue to rise for many years to come.

In addition, a qualitative modification has taken place in the manner in which manufacturing industries are adjusting to consumers’ environmental perceptions. In the past, most efforts to capitalize on the green movement centred on recycled products and environmentally friendly packaging materials, such as those produced from biodegradable plastics or from sustainably produced cellulose. Now, industries increasingly are looking directly at natural inputs in a more positive and pro-active manner: Natural inputs are considered not only as technically valid components, but also as elements that can contribute to the premium-pricing of final products because of their superior environmental attributes and their compatibility with socially responsible production and disposal requisites.

Changes in the regulatory environment also are playing an increasingly important role in encouraging industry to follow more environmentally sound practices. Of direct relevance to the natural fibres economy are a number of legislative provisions ranging from the banning of non-biodegradable plastic bags to the establishment of end-of-life recycling requisites for the automobile industry. These regulatory provisions are indicative of the pronounced trend in many high-income countries towards enacting legislation aimed at reducing environmental damage and the associated costs to society.

Commercial innovation to meet growing environmental concerns and associated regulatory provisions has not only built on appropriate research but has also stimulated the search for innovative solutions. While laboratory findings have increasingly demonstrated both the technical and economic benefits of the use of natural components in industrial products, it is clear that the scope for developing new methods and products that are respectful of the environment is vast. With continuing concern about environmental sustainability a given, research efforts will undoubtedly intensify, embracing not only product and process development but also the production, procurement and processing of the required natural components.

Aside from possible technical and cost advantages, it has become evident that products that can claim a role in contributing to environmental sustainability stand to be rewarded in the marketplace. This over-riding consideration is at least equally responsible for the growing success of environmentally friendly manufacturing as the concern for the longer-term sustainability of production. The trend towards an increased use of natural components has, however, been somewhat skewed in the direction of those materials produced in high-income countries which have significant manufacturing and research infrastructure and facilities. Thus, for example, the use of wood-based cellulose or cornstarch substitutes made rapid inroads into markets for plastic materials used in packaging.

There is considerable scope for further developing commercial opportunities for lesser-known natural products, for example fibres from developing countries. These natural fibre crops, such as sisal, are of vital importance to the livelihood and food security of farmers in some of the poorest regions of the world. As renewable raw materials, they require little if any chemical or other production inputs. At the same time, they provide employment for low-income populations in rural areas, while contributing to food security in times of drought. Although their traditional markets have shrunk, mainly owing to the deep inroads made by synthetics, these fibres possess the technical and economic characteristics suitable for use in higher value innovative applications, for example composites, building materials, furniture, packaging material etc. Moreover, the potential for using biomass and waste to generate biogas, animal feed and fertilizer continues to grow.

Under the umbrella of a project entitled “Unlocking the Commercial Potential of Natural Fibres” (henceforth referred to as the Project) funded by the Government of Germany and the Trade and Markets Division (EST) of the Food and Agriculture Organization (FAO) efforts are underway to make known the technical and economic attributes of hard fibres, in particular sisal. Increased focus by the public and private sector is needed to enhance the economically viable uses of these fibres on a global scale while benefitting the environment and contributing to income growth in developing countries. For example, there is strong potential for the greater use of sisal in the manufacture of industrial products that can appeal to environmentally-aware consumers.

However, it is clear that if the use of sisal and other natural fibres in innovative industrial applications is to expand, it should do so alongside the traditional uses in textile applications that have constituted their historical profile, one linking natural and social environments. The cultivation, processing and trade of natural fibres in traditional applications are part and parcel of the social fabric of the countries concerned. The fact that many of the major producing countries are in the developing world, and that cultivation is concentrated in some of the poorest countries, or in the very low-income areas of these countries where resources, information and technical support are scarce, means that change is often difficult to implement. Therefore, concerted efforts are underway under the Project to step up production, research, trade and manufacturing efforts that will help these countries break away from their current dependence on traditional markets alone.

In an increasingly environmentally conscious world, products made from natural fibres such as sisal or others having a natural fibre component are likely to be rewarded in the market place. Moreover, the trend towards natural components helps encourage the growth of sustainable agriculture: Their use promotes the adoption of environmentally friendly production and processing technologies, fosters economic development and strengthens the participation of smallholders in the value chain.

The Trade and Markets Division of the Food and Agriculture Organization of the UN is trying to bring together fibre producers, processors, researchers, scientists and industry representatives to explore the possibilities for working together towards more sustainable, environmentally-friendly and commercially-viable partnerships for the future.

# Factors impacting on market development and the economic significance of sisal

## Many favourable factors currently at play

Perhaps never before in the last several decades has the situation been as favourable as now for a significant increase in the use of sisal in innovative and value-added applications. The factors that currently are at play in enhancing demand have been present in the past on various occasions. But it is their current simultaneous presence that has given rise to the special circumstances that offer a vast potential for dynamic growth – that is, if stakeholders in the sisal economy are able to rise to the challenge.

The favourable factors that currently are contributing to a particularly enabling environment include:

* Heightened consumer concerns about the environment in the wake of a series of natural catastrophes;
* Legislative provisions governing manufacturing processes and specifications for consumer goods that are intended to reduce environmental damage and hazards;
* Laboratory research in both producing and consuming countries that has led to greater knowledge about the advantages of natural fibres, including sisal, in industrial applications;
* Unprecedented commercial innovation with natural fibres in non-traditional products, for example in automotive components;
* Relatively high and fluctuating prices of crude oil and its derivatives and concerns about the longer-term viability of production systems based on non-renewable resources;
* Improved opportunities for the dissemination of knowledge about sisal and other hard fibres (for example, through the Future Fibres website);
* Availability of a platform for the discussion of market issues and promotion of demand through the FAO Intergovernmental Group on Hard Fibres;
* International awareness of the positive economic, social and environmental impacts that a greater use of sisal may have in both producing and consuming countries and willingness to channel development resources into sisal improvement as evidenced by the support provided by the Common Fund for Commodities (CFC) and the Government of Germany, and;
* A renewed interest in sisal production and trade as a vehicle for economic growth and enhanced small holder participation in the value chain on the part of the authorities in the producing countries themselves.

While this unique combination of favourable factors gives rise to optimism, it would be best to avoid complacency regarding future developments. Indeed, if one compares past market expectations with actual results, it appears that in the past countries rarely took advantage of the opportunities that had been identified.

## Past market growth below expectations as use of sisal in new applications lags

Projections of world production, exports and imports of sisal and henequen from 2004 to the year 2012[[1]](#footnote-1) have been shown to be particularly accurate, especially as regards production. In contrast, market growth was repeatedly overestimated, as was the export performance of certain producing countries. The projections we refer to envisaged market stability approximately at the level of the year 2000, as the rising demand for imports by China was expected to offset the market erosion resulting from the introduction of synthetic substitutes and by the adoption of newer harvesting technologies using little or no twine. (Table 1)

At that time, it was believed that there was a potential for higher growth rates than those projected if the markets for sisal in the manufacture of higher value-added products such as paper pulp, carpet yarn and composites for the automotive industry were developed. Comparison of actual results for 2010 with the projections for 2012 indicates, however, that this potential was not realized and that there was, instead, an unexpectedly severe contraction in certain markets.

Analyses of market outlook were heavily influenced by assumptions regarding the expected inroads made by synthetic substitutes for sisal. It was thought that the demand for sisal baler twine in the United States would decline, while the fall in consumption in the European Union would be reduced. The Chinese market was expected to exhibit strong growth reflecting an increasing demand for fibre for industrial applications rather than for use as agricultural twine, the latter having suffered from the strong competition from domestic polypropylene production.

Instead, United States imports declined even more rapidly than expected while those by China far exceeded earlier expectations. In the European Union, net imports remained approximately at the 2000 level; the greater net imports of manufactures offset a drop of nearly 30 percent in raw fibre imports resulting largely from the displacement of the European spinning industry. Nevertheless, there are clear indications that the competitive position of sisal *vis-à-vis* polypropylene has improved since the middle of the last decade, at least concerning those applications where price is a significant determinant of demand and where substitution is possible from a technical point of view.

**Table 1 – Comparison of actual and projected trade values for sisal**(thousand tonnes)

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Actual** | | **Projected** | **Actual** |
|  | 1990-92 | 2000-02 | 2012 | 2010 |
| *Fibre exports* |  |  |  |  |
| Kenya | 29 | 16 | 12 | 20 |
| Madagascar | 10 | 9 | 5 | 8 |
| Tanzania | 5 | 12 | 11 | 12 |
| Brazil | 49 | 37 | 46 | 30 |
| Mexico | 0 | 0 | 0 | 0 |
| China | 1 | 0 | 0.3 | 0 |
| *World* | 99 | 80 | 109 | \*80 |
| *Manufactures exports* |  |  |  |  |
| European Union | 35 | 22 | 22 | 12 |
| Kenya | 1 | 4 | 4 | 0.4 |
| Madagascar | 2 | 1 | 1 | 1 |
| Tanzania | 16 | 2 | 3 | 6 |
| Brazil | 71 | 60 | 61 | 36 |
| Mexico | 7 | 4 | 7 | 1 |
| China | 0 | 4 | 4 | 7 |
| *World* | 155 | 113 | 115 | 80 |
| *Fibre imports* |  |  |  |  |
| European Union | 55 | 34 | 32 | a/21 |
| China | 8 | 13 | 36 | b/47 |
| *World* | 96 | 76 | 98 | \*80 |
| *Manufactures imports* |  |  |  |  |
| United States | 79 | 47 | 43 | 33 |
| European Union | 45 | 23 | 23 | 16 |
| ***World*** | **151** | **89** | **104** | **\*80** |

a/ Data refer to 2006, the last year for which sisal fibre trade is reported

b/ 2006 data  
\* Estimated

## AN Improved competitive position: Price factors associated with the markets for crude oil and derivatives

The current improved competitive position of sisal is rooted in the strong upward trend in the prices of crude oil. During the latter part of the 1980s, the annual average nominal price of crude oil ranged between US$ 12 and US$ 17 per barrel with a peak of US$ 20 in 1990. Prices were much lower during most of the 1990s, ranging between a low of US$ 12 in 1998 and a high of US$ 19 in 1996. However, a steady rise in prices – that has continued to the present – took place during the past decade. From an average level of about US$ 24 per barrel in 2000–02 prices continued to rise to more than US$ 50 in 2005, reaching a peak of US$ 97 in 2008. Although a weakening took place in the last two years of the decade, prices again rose sharply in 2011 to an average of more than US$ 110 in 2011. And though they currently stand at lower levels, prices of crude oil still remain high in historical terms.

Conventional wisdom once attributed considerable flexibility to the petrochemical industry in absorbing feedstock price increases largely because of the benefits of rising returns to scale and the vertical integration of the industry. Such factors allowed the industry to allocate cost increases to those sectors most able to absorb them, thus keeping prices relatively low in competitive markets or applications. While this behaviour may have been possible during the 1980s and 1990s, at least in the case of polypropylene (PP), indications are that starting in the early 2000s, price increases have been more difficult to contain.

Analyses of the co-movement of prices[[2]](#footnote-2) undertaken in the mid-2000s showed that PP prices adjusted to changes in crude oil prices within a period of about five months. From an annual average nominal level of US$ 803 per tonne in the 1980s, PP prices declined slightly to an average of US$ 771 in the 1990s. However, with rising oil prices in the 2000s, prices of PP more than doubled, averaging around US$ 1100 over the decade. The all-time peak prices of 2011 in crude oil and of the base chemical propylene were reflected in further PP price rises.

While the PP price increase undoubtedly favoured an increased use of sisal in those applications where substitution is technically possible, the improvement in the fibre’s overall competitive position was less than that suggested by the rise in synthetic fibre prices. As pointed out in studies of the co-movement of prices, increases in the price of one of two close substitutes show relatively equal increases to those of the other. Indeed, it was found that in competitive applications sisal prices tend to adjust to PP prices over a period of some ten months.[[3]](#footnote-3) Thus, the strengthening of prices during 2011 may be in part a reflection of the co-movement of quotations in response to higher PP levels.

## AN Improved competitive position associated with environmental concerns

With rising crude oil prices in the 2000s and the associated increases in PP, the need to document the environmental advantages of natural fibres, such as sisal, became imperative. The relative environmental implications of using natural fibres versus synthetics were first addressed at the international level by the FAO Intergovernmental Groups on Hard Fibres and on Jute, Kenaf and Allied Fibres in the early 1990s. At that time, however, there was little scientific research on the subject and quantitative results for assessing environmental impacts were sorely lacking. Most environmental and sustainability discussions were based then on qualitative information.

Nevertheless, as early as the start of the 1990s, comparative analysis found that the production of natural fibre required less than 10 percent of the energy used for the production of PP fibres. When the use of fertilizer was included in the calculations, the energy requirement increased to approximately 15 percent of that for PP fibres. In addition, the impact of waste generation (air and water pollution and solid waste production) was found to be higher for synthetic fibres, even if water pollution in the primary processing of natural fibres was recognized to be relatively high. This information was widely disseminated among the main players of the natural fibres industries, but failed to reach a wider audience concerned with environmental issues.

It was not until the middle of the last decade that concerted efforts were made to ascertain – on the basis of scientifically demonstrated results – the true environmental advantages or drawbacks of natural fibres in various uses.[[4]](#footnote-4) These analyses made use of Life Cycle Assessment (LCA) to quantify the environmental impact of products over their entire life cycle, from raw material to processing and to final product disposal. This work laid the groundwork for follow-up actions both in terms of research as well as of applied technology.

The production of sisal and henequen fibres was found not to use excessive amounts of agrochemicals and only limited quantities of pesticides. The most severe impact on the environment in the fibre extraction process was identified as that deriving from the use of energy- consuming machines and from the accumulation of biomass waste and waste water. These results worked to stimulate research regarding the use of sisal waste for the production of biogas, fertilizer, animal feed, paper pulp and flume tow recovery in East Africa and Brazil. With support from the CFC, the first plant for the production of biogas from sisal waste was opened in Tanzania, serving as an example of how the transfer of technology to other developing sisal producing countries can work toward containing environmental degradation while generating much-needed energy and improving the sector’s economic returns.

## INCREASED RESEARCH ON INDUSTRIAL APPLICATIONS FOR SISAL

As regards the various industrial applications for sisal, it is only recently that significant research has been conducted on the technical and economic implications of using sisal in various innovative applications, in particular as a component in industrial products. Moreover, the quantitative information regarding the potential markets for the fibre when used in new applications continues to be inadequate. This no doubt reflects the limited economic importance of these fibre crops in developed countries where, until recently, most of the research was conducted and where research heretofore focused almost exclusively on domestically available natural fibres and their residues, such as flax, hemp, cotton, wood chips, sawdust and rice husk.

Among the new applications which attracted early interest was the possible use of sisal for the production of *paper and pulp.* Various attempts to develop this market have to date been unsuccessful because of problems of scale and because of current competitive conditions; the high cost of chemical recovery so far has impeded the establishment of economically viable small-scale pulping units for fibre crops as a substitute for wood-based products. Moreover, when made from sisal, the product could not command a premium as speciality pulp and paper. Further research into the possibilities of utilizing sisal fibre and biomass for paper pulp was pursued under the CFC project CFC/FIGHF/07 concerning product and market development for sisal and henequen. However, in the course of project implementation of the plan to establish a pilot operation for producing pulpable fibre was abandoned because of the need for large-scale operations, the substantial financial requirements and concerns regarding the ready availability of the raw materials.[[5]](#footnote-5)

With regard to *building materials,* the use of renewable resources has been recognized as contributing to sustainability by slowing the rate of deforestation for wood construction products. Thus, fibres were seen as offering potential in such uses as fibreboard, insulation, reinforcement or filler in lightweight concrete, bricks and building blocks and as a substitute for asbestos cement. However, the availability of supplies and competitive prices relative to alternative materials, for example wood chips, were likely to determine the choice of raw materials. Nevertheless, continued strong interest exists in fibres’ longer-term potential for use in building materials, and in recent years considerable laboratory research has been undertaken. Indeed, an FAO mission fielded to Haiti under Project GCP/INT/115/Ger concluded that there were excellent opportunities for using sisal in the manufacture of sisal-reinforced composite materials for the production of roof tiles and other construction materials such as door and window frames.[[6]](#footnote-6)

The replacement of asbestos in cement by sisal is a particular aspect of the market for construction materials that has gained ground as the prohibition of asbestos has gained momentum, particularly in some large populous countries, and is expected to continue to do so. Under CFC project CFC/FIGHF/15, implemented in 2009, concerning the replacement of asbestos by sisal in cement, extensive research was carried out by three universities in Brazil (UFCG, USP and UNESP) and the resulting studies were found to be comprehensive, well thought-out and – drawing on long years of research experience in composite applications – included the fundamental aspects of material characterisation[[7]](#footnote-7). However, to date the results of this research have not had any real relevance for the market because of a lack of economic viability under existing market conditions.[[8]](#footnote-8) Nevertheless, it appears that once existing legislation in Brazil and other countries where the use of asbestos continues to be permitted is changed, there will be significant longer-term opportunities for sisal as a replacement of asbestos in cement construction materials.

An area that first attracted considerable interest in the middle of the last decade was the possible use of natural fibres in synthetic polymer *composites*, particularly for the automotive industry. While specific tests had not yet been carried out for sisal, the results obtained with fibres produced in relatively higher-income countries such as flax and hemp indicated that the substitution of fibreglass led to a comparatively small reduction in non-renewable energy requirements during the production phase. On the contrary, the use of natural fibres had a positive environmental impact owing to its lower weight and lower fuel consumption during use. In addition, composites reinforced by natural fibres were recognized as having advantages in the end-of-life phase.

To a certain degree, the transformation of these research results into commercial reality has already taken place, for example in Brazil where Ford is using sisal in various automobile parts. As reported at the FAO Consultation on “Unlocking Commercial Fibre Potential in Developing Countries”, held in Salvador, Bahia in November 2011, the environmental advantages of using sisal in Ford automotive parts was heavily reinforced by the positive message to prospective buyers regarding economies in fuel use. Further action is needed to promote the opportunities for the use of sisal in synthetic polymer composites, not only in the automotive industry, but also in a wider range of applications.

There is, however, a need to provide greater information regarding the multitude of innovative applications of natural fibres from developing countries that exist amd which go beyond their traditional uses. As not much information about this sector has been available, one of the main objectives of this publication is to inform government and industry representatives – and the public at large – of the current state-of-the-art research that exists on natural fibres in innovative applications. It is hoped that this information (see Section IV) will give rise to new partnerships that will lead to longer-term economic, social and environmental benefits for both producers and consumers. In the process of enhancing the use of sisal in non-traditional applications, it is expected that real contributions may be made to improving income, value-chain participation and food security for vulnerable rural populations in some of the poorest areas of the world, many of which are located in the world’s least developed countries.

# The economic significance of sisal

Sisal is a fibre produced in some of the lowest-income areas of the world. The countries that produce the fibre include several that are classified as being Least Developed Countries (LDCs), that is those where average annual per capita gross income does not reach US$ 750. The sisal producing countries in this category include Haiti, Mozambique and Tanzania, the three beneficiary countries targeted under Project GCP/INT/115/Ger.

The special peculiarity of sisal is not only that its cultivation originates in many LDCs, but above all that these crops are often located in particularly arid areas where other plants are unable to survive because of the exceptionally arduous climatic conditions. The rural populations of these areas are therefore particularly dependent on sisal, which represents one of the few sources of dependable cash income. In periods of pronounced drought, sisal offers the only hope of maintaining sufficient purchasing power to access food supplies. Thus, while other crops that are grown mainly for household consumption are destroyed by the harsh climate, sisal’s hardiness and its consequent income-earning potential is able to provide some assurance of food security. This is the case not only in producing countries of the LDC category, but also in the world’s largest sisal producer, Brazil. In this country, production of sisal is concentrated in the very low-income, arid areas of the north-eastern region, where alternatives for rural income generation are limited or non-existent. Given the physical location of sisal and henequen fibre production in some of the most arid areas of the countries concerned, and given the particularly low-income levels of farmers and workers in these locations, sisal cultivation provides one of the few viable agricultural production alternativesto generate income and supplement on-farm food production. In the light of its drought resistance, sisal has acquired heightened significance as a crop contributing to food security.

The contribution of sisal to the well-being of vulnerable rural populations has been eroded over past decades. A pronounced downtrend in sisal production reflects the drop in demand for the fibre in traditional uses, primarily baler twine. In such traditional uses, competition from synthetic polypropylene (PP) twines as well as from changes in bailing technology made sisal a less attractive product. Over the past several decades, the reduction in the production and exports of sisal and sisal products has affected mainly developing countries adversely. For example, in Brazil the market contraction resulted in the loss of more than 730 000 rural jobs, and rural employment and earnings from sisal also declined in other producing countries, particularly in Africa. The continuing slide in the traditional markets for sisal and henequen has had severe adverse effects on production, employment and farmers’ income. A reversal of this trend is considered essential if farmers are to find new employment opportunities and to develop a “food security safety net”, while at the same time contributing to income generation and export earnings at the national level.

As far back as the early 1990s, there was international awareness of the need to address the problems of the sector caused by the rise of synthetics and the consequent displacement of sisal in traditional uses. The shift in emphasis in international commodity policy discussions from price stabilization to market and product development provided the basis for a new approach to resolving commodity problems, one that was based not only on government commitments but also on partnerships with the private sector. With the establishment of the Common Fund for Commodities (CFC) and the designation of the FAO Intergovernmental Group on Hard Fibres as the international commodity body (ICB) responsible for project prioritization, the stage was set for channelling international resources to sisal development activities; this was seen as an essential part of an attempt to use research and development projects to improve commodity markets and strengthen the capacity of developing countries and small farmers to participate in trade. While not all of the objectives were achieved, significant results were obtained in a number of areas which greatly improved the capacity of small farmers to participate in the sisal value chain. Considering the Common Fund Project CFC/FIGHF/07 concerning product and market development for sisal and henequen, special mention should be made of the impacts on *smallholder cultivation of sisal* in the drought-prone areas of Tanzania. Immediate results under the Project were promising, with increasing numbers of farmers undertaking the intercropping of sisal with food crops and thus benefiting from the “safety net” offered by the crop in periods of drought.

*The Tanzanian experience*

It is illuminating to consider the experience regarding development of sisal cultivation in Tanzania, one of the world’s major sisal producing countries and also a LDC. The incentive to grow sisal in the drought-prone areas of Tanzania can be seen by even rough yield/returns calculations: Prior to sisal cultivation, a hectare of land (if not affected by drought) yielded roughly 20 bags of maize valued at an average price of Tshs 200, thus earning about Tshs 400 000 annually, or the equivalent of US$ 266. Under sisal cultivation, annual earnings rose to some Tshs 1 920 000, or US$ 1 280 per hectare.

In Tanzania, a smallholder sisal scheme began with plantings in 1999. The total area under smallholder sisal in estates increased from 32 hectares in 1999 to 5 129 by December 2009 when the Project concluded. Over that period, smallholders invested the equivalent of nearly US$ 1.5 million in planting and maintenance. Access to financial resources was facilitated by the release of land leases by Katani Ltd for transfer by the Government to the Tanzania Sisal Board (TSB); the land was to for allocation to smallholders who acquired title to it land for the period of the lease. The entire area released under the smallholder scheme has now been planted and even farmers outside the scheme were developing land for sisal cultivation. Following the approval of the planned expansion, the financial resources for the development were provided from the district budget.

Another indicator of the economic significance of sisal cultivation in Tanzania is the rise in marketable production, reflecting not only increased plantings but also higher yields. Under the CFC projects, field trials indicated that higher-density planting (though still not at the levels that would have been achieved if whole-plant harvesting had been adopted) would contribute to improved returns. Those findings won the interest of small farmers, with the result that there were further plantings, at densities higher than 6 000 plants, as opposed to the traditional density of 4 000 plants per hectare. Due to both the increase in cultivated areas and the higher yields, the production of fibre by smallholders increased from 1 090 tonnes in 2003 to more than double that figure at the end of the decade.

Aside from (or perhaps because of) the immediate impact on the economic condition of the area’s smallholders, both government and the private sector developed a new perception about the value of sisal and the possible market opportunities deriving from new uses of the fibre. Indeed, there is evidence that the sisal development activities undertaken over the past decade, along with generally more favourable prices, have encouraged industry stakeholders to increase investment and new plantings in Tanzania to an extent not matched in many years past.[[9]](#footnote-9)

Among the potential new uses of sisal in Tanzania is that resulting from the development of process technology for the utilization of sisal waste to generate biogas. Under a favourable enabling environment (which means one including adequate credit facilities), this development can have substantial beneficial economic, social and environmental impacts. It has been demonstrated that it is technically feasible to produce biogas from sisal waste. The energy generated could be used initially by the plantations themselves to provide power to processing facilities and other estate infrastructure at substantial savings compared to power provided by the national electricity grid. Subsequently, power and gas could be provided to the houses of estate workers for domestic use, a development with evident social and health benefits that could also act as an incentive to encourage labour to return to work on sisal plantations rather than to continue to migrate to over-populated and under-serviced urban areas. Eventually (that is, for as long as production could attain the scales required by the national provider[[10]](#footnote-10)) excess energy could even be sold to the national grid.

In addition, the diffusion of the process technology developed in Tanzania (involving hammer mill operations and biogas facilities) would not only contribute to the generation of renewable energy but was also likely to reduce the land and water pollution caused by traditional manufacturing operations.[[11]](#footnote-11)

# State-of-the-art research on natural fibres in new applications[[12]](#footnote-12)

## INTRODUCTION

Natural fibres have been described in literature as coverage for the body and the construction of housing since early 4000 BC in Europe, 3000 BC in Egypt and 6000 BC in China. Flax was the first vegetable fibre to be used for clothing by humankind.

The continual growth of the consumption of non-renewable resources in the world, such as petroleum, as well the renewable ones such as water, is a matter of constant concern in scientific circles. Another problem under intense discussion is that of climate change due to human activities, mainly carbon dioxide emissions. The growing needs of humankind, due largely to increasing rates of world population growth and adoption of modern life-styles, has meant a substantial increment in the per capita consumption of synthetic materials. Not surprisingly, then, recent environmental pressures have led many increasingly to attribute major importance to the use of renewable materials in the manufacture of industrial components.

Natural fibres of one kind or another are produced in almost all countries, and usually are referred as lignocellulosic materials. In tropical countries, such as Brazil (several crop fibres), Colombia (fique), Ecuador and Philippines (abaca), India (coir and jute), Pakistan and Bangladesh (jute and coir), China (ramie), there exist a large variety of natural fibres with different mechanical, physical and chemical characteristics. The list of fibres with potential or proven commercial applications which are grown in those countries includes sisal, jute, phormium, fique, abaca, coir and ramie. In temperate climate countries, flax and hemp are the most representative. Cultivation of kenaf has recently been introduced in several countries, and nowadays is grown in places such as the United States, Malaysia, Bangladesh, Thailand, etc. (see Table 2). Cotton, the most important natural fibre in terms of volume and value, is not covered in this analysis because its potential innovative applications are already well-known and research and promotion activities for this fibre are done regularly both by private and public sector institutions as well by the International Cotton Advisory Committee (ICAC), the international organization charged with responsibilities for the sector.

Lignocellulosics residues also represent an important source of raw materials for the development of new materials to replace man-made, non-renewable ones. Such residues include sugar cane bagasse and leaves, which account for the largest volume, wood residues from exploitation and industrialization, and straw from several grain crops.

**Table 2: Fibres and countries of origin**

|  |  |
| --- | --- |
| Sisal | Brazil, East Africa, Haiti, Venezuela, Antiqua, Kenya, Tanzania, India |
| Flax | Poland, Belgium, France, Spain |
| Hemp | Poland, China, Hungary, France, Romania |
| Sun Hemp | Nigeria, Guyana, Siera Leone, India |
| Ramie | Honduras, Mauritius Islands, China |
| Jute | India, Egypt, Guyana, Jamaica, Ghana, Malawi, Sudan, Tanzania, Brazil |
| Kenaf | Iraq, Tanzania, Jamaica, South Africa, Cuba, Togo, USA, Thailand |
| Roselle | Borneo, Guyana, Malaysia, Sri Lanka, Togo, Indonesia, Tanzania |
| Abaca | Ecuador, Philippines, Colombia |
| Coir | India, Sri Lanka, Philippines, Malaysia, Brazil |
| Curaua/Kurowa | Brazil, Colombia, Venezuela, Guyana |
| Fique | Colombia |
| Piaçava | Brazil |

Environmental and economic concerns are stimulating research in the development of new materials for construction, furniture, packaging and automotive industries. Particularly attractive are the new materials derived from natural renewable resources which prevent further stress on the environment such as that caused by the depletion of already dwindling wood resources from forests. Examples of such raw material sources are annual-growth native crops, plants and fibres that are abundantly available in tropical regions. These plants and fibres (such as jute and sisal) have been used for hundreds of years for many applications, including ropes, beds, bags, etc. If new uses of fast growing native plants can be developed for high value, non-timber based materials, they could constitute a tremendous potential for creating jobs in the rural sector.

Additionally, these renewable, non-timber based materials could further reduce the use of traditional materials such as wood, minerals and plastics in some major applications. There is tremendous interest on the part of the pharmaceutical industry in exploring the rain forest for new drugs. So far, however, there has been little interest in exploring the rain forest for fast-growing native plants as a fibre source. In applications such as ropes, new synthetic materials such as nylon have replaced locally-grown fibres such as sisal and jute. The growing interest that exists today in saving forests and, at the same time, in creating rural employment therefore means that new materials must be developed so that locally available non-wood renewable resources can be used. The advantages of these plants are that they are fast-growing and renewable and sometimes can also be a source of food supply for animals and even humans.

Environmental concerns and increasing competitiveness are pressuring companies to make more (quantity and quality of products) with less (raw materials, energy, environmental impact, etc.). The intensity of use of the materials must take into account the cost of manufacture, use, reutilization, recycling and final disposal. In other words, the efficiency of the conversion of natural resources must be increased so as to extend the useful life of products, to improve recycling potential, and to use environmentally sound technologies that are also healthier for workers and consumers. In this sense, too, the attractiveness of composite materials with a natural fibre component is enhanced.

## Natural fibre composites

Composites systems consist of the association of one substance to a second or third substance, which can be a load or a reinforcement, that can be continuous, discontinuous, short, long, in the form of dust, spheres, and so forth. The result of this mixture is a synergic effect on the global properties of the system derived from the individual properties of its components. The composites sector is expected to become the most important segment of the plastics industry. The prospects for servicing world markets – offering a favourable association of product, quality, performance and cost – are immense.

In this context, natural fibres are of particular interest: They are abundant, renewable, low-density, and compared with other polymeric materials they have an extremely favourable standing from the point of view of the resistance-weight relationship (a specific module). Natural fibres have composites that are guided by cost and which are attractive to markets because of their low price. But other groups are guided by performance with properties that dictate the market. It is into this last group that the possibility of inserting composites reinforced with natural fibres can be inserted and for which enormous growth can be envisaged over the next decades.

Additionally, the use of natural fibres in thermoplastic or thermosetting composites could help, in the longer run, to reduce one of the greatest problems facing tropical countries, an agricultural exodus that leads to the marginalization of large populations of unqualified workers who flock to the cities in search of jobs for which they have neither the qualifications nor the experience. If incomes from agriculture were to be increased, these people would remain in the fields, with the result that more crop fibres, and their by-products, will be produced. Such a development would be particularly advantageous in areas that are economically depressed.

Combining agro-fibres (lignocellulosics) with other resources represents a strategy for producing advanced composite materials that takes advantage of the properties of both types of resources. It allows the scientist to design materials based on end-use requirements within a framework of cost, availability, recyclability, energy use and environmental considerations. Lignocellulosic resources have low densities, are low in cost, renewable, non-abrasive, have excellent specific mechanical properties, and are potentially outstanding reinforcing fillers in thermoplastic composites. The specific tensile and flexural modulus of a 50 percent (by volume) sisal-PP composite compares favourably with a 40 percent (by weight) glass fibre-PP injection moulded composite. These new composite materials are finding innovative applications and fresh markets never before envisioned by the agro-industrial sector anywhere.

Natural fibres (Amar *et al*., 2005) are generally lignocellulosic in nature, consisting of helically-wound cellulose microfibrils in a matrix of lignin and hemicellulose. According to a Food and Agricultural Organization survey, Tanzania and Brazil produce the largest amount of sisal. Henequen is grown in Mexico. Abaca is grown mainly in the Philippines. The largest producers of jute are India, China and Bangladesh. Presently, the annual production of natural fibres in India is about six million tonnes as compared to worldwide production of about 25 million tonnes. Table 1 shows the various natural fibres and their countries of origin.

These natural resources play an important role not only in the growth of the gross domestic product (GDP) of any country, but also in the social and economic development of developing third-world countries. The worldwide trend currently is to use such resources to the maximum extent through new technologies and new products. This in turn creates new jobs, generates more income and thereby improves the standard of living of the people within these countries.

## TECHNOLOGIES FOR NATURAL FIBRE BASED COMPOSITES

The following are examples of the technologies used in the production of various types of natural fibres-based composites (Leao *et al.,* 2010).

Name: Fibreboards

* Substrate: Non-woven and fabrics (hybrid fibres and wood and polyester).
* Matrix: Thermosetting water soluble phenolic (PF or UF) resin system.
* Technology: Compression moulding through the use of a hydraulic press.
* Applications: Boards for flooring, roof, internal walls and panels for automotive and furniture industry (a replacement for solid wood).

Name: Woodstock™ type has been largely applied in the automotive industry, mainly by the Italian company, Fiat.

* Substrate: Natural fibres non-woven mats and granulated natural fibres and wood flour.
* Matrix: Unsaturated polyester and thermoplastic (HDPE and LDPE).
* Technology: Compression, extrusion, flat dye.
* Applications: Automotive interiors, furniture, shoes, etc.

Name: Medium Density Fibreboard (MDF)

* Substrate: Use of residues such as bagasse mixed with other agricultural fibres.
* Matrix: Thermosetting resin (tannin, UF, MDI or PF).
* Technology: Conventional defiberization and mat formation.
* Applications: Replacement of solid wood.

Name: Pultrusion profiles

* Substrate: Natural fibres (jute, sisal and curaua) in mats, fabrics or hybrids;
* Matrix: Thermosetting liquid resin.
* Technology: Conventional pultrusion (substitute for glass fibres).
* Applications: Different profiles as a replacement for solid wood and aluminium.

Name: Long Fibre Reinforced Thermoplastic (LFRT)

* Substrate: Natural fibres (sisal and curaua) in roving or twine with a small number of filaments.
* Matrix: Thermoplastic polyolefins.
* Technology: Extrusions with the side feeder of the twines continuously, ideal for profiles (substitute for glass fibres).
* Applications: Different profiles as a replacement for solid wood and aluminium (window and door frames).

Name: Moulded products

* Substrate: Non-woven mats (treated and non-treated).
* Matrix: Unsaturated polyester resin.
* Technology: Resin Transfer Moulding (RTM) and BMC (Bulk Moulding Compound).
* Applications: Door siding, components and parts for automotive industry, instrument panels, engine covers, etc.

Name: Granulate of natural fibres blended with thermoplastic resin (HDPE, PS, PP and LDPE)

* Substrate: Natural granulated fibres.
* Matrix: Thermoplastics resin (up to 80-90 percent).
* Technology: Melting and composting in twin-screw extruder.
* Applications: Pallets, packages, appliances, etc.

Name: Thermoplastic residue boards

* Substrate: Agriculture residues (straw, bark, fibre fines, bagasse, etc.).
* Matrix: Non-identified thermoplastics (municipal solid waste).
* Technology: Grinding, melting, extrusion (single-screw) and compression moulding.
* Applications: Replacement of solid wood in mobile toilets, cabins, exterior furniture wall panels, wire electric coils, etc.

Name: Hybrids of natural and glass fibres

* Substrate: Natural fibres/glass fibres, glass fibre interiors/natural fibres exteriors.
* Matrix: Unsaturated polyester and epoxy resin.
* Technology: Contact moulding/RTM.
* Applications: Low-cost houses, boats, water containers, storage grains, etc.

Name: Tecnomix (Developed by Toro Ind. Ltd. and UNESP)

* Substrate: Natural fibres (sisal, jute, coir, curaua**L**and ramie). Non-woven mats.
* Matrix: Thermoplastic resins (polyethylene, polypropylene).
* Technology: Non-woven mats and compression moulding.
* Applications: Interiors for automotive industry such as package tray, door sides, roof, etc.

Name: Roof shingles

* Substrate: Natural fibres (sisal, jute, coir, and ramie. (Non-woven mats or fibres bundles).
* Matrix: Cement and blast furnace slag mortar reinforced with strand fibres.
* Technology: Conventional and fast curing (CO2) concrete.
* Applications: Civil engineering replacement of asbestos fibres and concrete, etc.

Name: Cellular Concrete

* Substrate: Lignocellulosics residues (rice, barks, natural fibres

Such as sisal, jute, coir, curaua, sugar cane, bagasse, ramie, etc.)

* Matrix: clay, Al2O3, CaO and residues.
* Technology: Sinterization at high temperatures (over 1 600 °C, and formation of macro-pores).
* Applications: Interiors in high buildings for weight reduction - density = 0,3.

The use of recycled post-consumer thermoplastic is another possible means of reducing the cost of these composites. Thermoplastic post-consumers in blending with any lignocellulosics material represents enormous environmental economy, and results in lesser virgin resin demand, consequently reducing the pressure on petroleum. This technology merges with ecology, where the biggest concern is sustainability of the ecosystems on the planet. In addition, there are economic considerations with companies continuously aiming at reducing the costs of processes and/or products.

The association between the two strategies can be termed “Ecomenes”, which consists of the use of a material with ecological characteristics that is competitive in relation to its conventional countertypes, for example sisal vis-à-vis fibreglass or polyurethane. Ecomenes can be defined as the use of natural resources in an ecologically friendly way. Thus, for example, natural fibres present a bigger modulus of elasticity when compared to steel. This is particularly important for the automotive industry which aims at the reduction of vehicle weight. Another positive aspect of natural fibres concerns the ISO 14,000, where life-cycle analysis will be decisive in the future for comparisons between natural fibres and glass fibres. In this regard, composites reinforced with natural fibres have a distinct advantage in relation to energy consumption, emission of effluent, toxicity (for both workers and consumers), ease of final disposal, repetitive recycling, and so forth. Such composites are expected to be seen by consumers and industry as a promising option to replace non-renewable counterparts. For example, it is currently estimated that in Brazil the potential use of natural fibres could amount to something such as 40 000 tonnes per annum for the automotive industry alone, the equivalent of approximately 23 kg/auto of natural fibres. And this without even considering their potential use in other new markets such as civil construction and electronics (Leao, 2005).With the exception of those applications where temperatures must be increased to 200oC, all automotive applications appear suitable for replacement by natural fibre.

## Composition of natural fibres

Lignocellulosics fibres contain mainly, lignin and cellulose. The sources of these substances include agricultural and agro-industrial residues, agricultural fibres, aquatic, grassy plants and other vegetal substances. In general, lignocellulosics have been included in the term biomass, but this term has other applications as well since it involves, for example, feathers, fur and animal bones. Lignocellulosics, also is called phytomass, because they are produced through the photosynthesis; or alternatively "biobased", meaning based on biological processes. But the term lignocellulosics is better. These natural fibres are on together with a phenolic natural polymer, lignin, which is commonly present in the cellular walls of vegetal fibres, and which gives lignocellulosics its name. One exception is that of the cotton linter, which does not contain lignin.

Vegetal fibres are classified in accordance with its place of origin in a plant: 1) bast refers to fibres located in the stem; 2) leaf fibres run in the direction of the length of leaves of a plant, such as grass, and are related to hard fibres; and 3) other fibres come from the hair of seeds, mainly cotton. These are the principal sources of vegetal fibres. Vegetable fibres exist in about 250,000 species of superior plants, but fewer than 0.1 percent of these are commercially important as fibre sources. The fibres in bast and leaves are integrated into the structure of the plants, to which they supply support and resistance; indeed, these fibres are situated next to the external ring of a plant, fortifying its support and preventing their bedding (wheat, rye, etc.). They run in the direction of stem length. The separation of these fibres for the removal of their natural gum can be done by different methods (mechanical, biological and chemical) that can affect the quality and the length of fibres. The long leaf fibres contribute to the resistance of the leaves.

The chemical composition of the principal commercial fibres are given in Table 3. The purest is cotton (90 percent cellulose) while the others are between 70 and 75 percent cellulose, depending on the processing method used. Ramie contains about 95 percent of cellulose. Kenaf and jute contain high levels of lignin. Another important factor that influences the final properties of natural fibres (Leao, 2010) is the presence of extractives, (pectins, hemicellulose and lignin), which are of variable quality and amount. The dimensions of natural fibres represent another important aspect. The physical properties vary sufficiently in function of the specific variety, place of growth, time of harvest, localization in the plant, methods of processing, and so forth.

**Table 3 – Chemical composition of selected vegetable fibres (percent by weight)**

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Fibres** | **Cellulose** | | **Hemicellulose** | | **Pectins** | | **Lignin** | | **Extractive** | |
| Flax | 71.2 | 18.6 | | 2 | | 2.2 | | 6 | |
| Hemp | 74.9 | 17.9 | | 0.9 | | 3.7 | | 3.1 | |
| Jute | 71.5 | 13.4 | | 0.2 | | 13.1 | | 1.8 | |
| Kenaf | 63.0 | 18.0 | | 2.1 | | 17.0 | | 2.0 | |
| Ramie | 76.2 | 14.6 | | 0.6 | | 0.7 | | 6.4 | |
| Abaca | 70.1 | 21.8 | | 0.9 | | 5.7 | | 1.8 | |
| Sisal | 73.1 | 13.3 | | 2.6 | | 11.0 | | 1.6 | |
| Coir | 43.0 | 0.1 | | - | | 45.0 | | - | |
| Cotton | 92.9 | 2.6 | | 2.6 | | - | | 1.9 | |
| Curaua | 70.7 | 10.7 | | 4.5 | | 11.1 | | 3.0 | |

**Source:** Leão, 2005

A major objective in producing a composite based on vegetal fibres consists in giving it uniform characteristics and thereby producing a new material in the technical meaning of the word. A material is usually defined as a substance with properties that are uniform, continuous, predictable and reproducible. On the other hand, an engineering material is defined simply as a material used in construction. Wood and other lignocellulosics have been used as engineering materials because they are economic, require little energy for processing, are renewable, and are reasonably strong. On the basis of this definition, therefore, lignocellulosics are not considered materials because they do not possess these characteristics. But if this is true for solid lignocellulosics, such as wood, it is not necessarily the case for reconstituted composites made from lignocellulosics.

The key factor in producing composites based on natural fibres is temperature. The temperature of cellulose decomposition (approximately 220 °C) represents the upper limit in the temperature of processing, allowing four main plastic commodities (PE, PP, PVC, ABS and PS) to be used without degradation problems. The resultant blends can be processed subsequently for the manufacture of diverse products, using techniques already known such as extrusion, injection moulding, pultrusion and hot-pressing. Inorganics such as mica, talc and clay represent intermediate materials often used to give stability; when used together with natural fibres and polyolefin matrix their action expresses the relationship that takes the average diameter of flakes and divides it by the average thickness. This is referred to as flake aspect ratio, or the relation of the aspect of the fibre. The analogous ratio for fibres is the average length of the fibre divided by the diameter (fibre aspect ratio). When values are close to 100, as is the case in wooden fibres, it means that the material has an excellent potential as a filler and reinforcement.

## Principal ADVANTAGES OF NATURAL FIBRE COMPOSITES

The main advantages to having composite materials based on natural fibres are:

* Replacement of man-made fibres (glass and asbestos). In many countries, environmental restrictions have been placed on final disposal for post-consumer products based on glass fibre, and some even have forbidden its utilization, as for asbestos.
* Reinforcement of conventional thermoplastics and thermosetting resins with natural fibres or polymers can reduce the demand for petroleum-based products (carbon-based).
* Substitution of solid wood by plastics reinforced with wood or other natural polymers can help to reduce deforestation. They also have mechanical advantages over traditional wooden products.
* Suitable for building profiles that can be used to replace aluminium in civil construction in coastal cities.
* Enhancement of fibre quality in end-use applications through the use of better hybrids or varieties based on genetic knowledge such as fibre percentage and mechanical strength.
* Improved agricultural productivity and fibre quality through the use of better extraction processes.
* Development of new machines (smaller, better quality and improved safety) to process and industrialize natural fibres directly in the field.
* Providing a new source both of income and raw-materials to the rural population in economically deprived areas.
* Lower cost when compared to man-made fibres; the price by weight is much lower for products made with natural fibres when compared to their synthetic counterparts.
* Phytomass is totally utilized, although for many crop fibres a very low percentage is represented by the fibres itself, and the rest represents a new source of raw materials or feedstock for natural chemicals.
* Environmentally friendly methods of production, harvesting, processing and recycling or final disposal.
* Renewability. By definition a natural resource is renewable if its cycle can be completed in a period compatible to the human cycle.
* Resistance. Products made with natural fibres do not break when processed, in contrast to comparable substances such as glass fibres. This makes more intense processing possible.
* Release into the environment of only harmless residues when incinerated for energy recovery or final disposal, without the presence of either sulphur or heavy metals.
* Absorption of renewable carbon (green carbon) contributes to a reduction of climate change.
* Automotive parts made of natural fibres are resistant to fractures, giving a high standard of passive safety in case of collision or burning.
* Non-abrasive when processed by conventional machinery.
* Low density with a high specific modulus, meaning that these substances represent one of the strongest types of modulus and rank even higher on the chart than steel.
* Their high resistance and low elongation makes them desirable for certain applications.
* Low-energy consumption when processed, due to low-temperature requirements and flexibility.
* Possible applications with higher levels of reinforcement (up to 90 percent) with new technologies such as extrusion and injection moulding.
* Can satisfy environmentalist pressure calling for the greater utilization of natural renewable resources as a means of reducing the use of man-made materials.
* Better efficiency, because of energy balance, in converting raw-materials into products when compared to other man-made fibres.
* Products are competitive when considered in terms of life cycle analysis (see ISO 14.000).
* Appropriate for a national strategy to create rural jobs in economically deprived areas.
* Good mechanical properties relations: Weight versus resistance, which in the case of the automotive industry helps to reduce fuel consumption.
* Composites/*Ecomenes –* The concept of having a product that is ecological, but also economically competitive. Oikos (environment) – menes (way), a mixing of ecological and economics.
* Recyclability. Composites based on natural fibres can be recycled many times without significant loss of any mechanical properties.
* Greenhouse effect is reduced by the utilization of natural fibres-based products, since their production is based on the green carbon cycle, as called for by the Kyoto protocol.
* Marketing. The market concept must be revised since the general view is, mistakenly, that lignocelullosics-based composites are “low-tech” when, in fact, the opposite is true since these products in many cases are manufactured by the same machinery developed to work with products made with man-made composites such as polypropylene fibres.

## composites applications AND cost implications of RELATED TECHNOLOGIES

The following is a list of technologies or approaches having implications for the increased use of natural fibres and for the utilization of the resulting phytomass. Some are industrial processes, and others simply provide data that will favour environmentally sound products of various types:

* RTM - Resin Transfer Moulding
* SMC - Sheet Moulding Compound
* BMC – Bulk Moulding Compound
* Extrusion and Injection
* Thermoforming of non-woven mats
* Woven mats
* Bionanocomposites
* Life cycle assessment
* Energetic and carbon balance
* Cement matrix (asbestos replacement).
* Briquetting
* Pulp and paper
* Filters (cold plasma and corona discharge)- These are useful for the selective absorption of oil (spills) and enhancement of adhesion plastic and lignocellulosics.

Totally new types of composite materials can be fabricated by combining different resources. It is possible to combine, blend, or alloy lignocellulosic or agro-based fibres with materials such as glass, metals, plastics and synthetics to produce new classes of composite materials. The objective is to combine two or more resources in such a way that a synergism between the components results in a new material that is superior to its individual components.

One of the biggest new areas of research in this field is in combining natural fibres with thermoplastics (Sanadi *et al*., 1994 a,b,c). Since prices for plastics have risen sharply over the past few years, the addition of a natural powder or fibre to plastics provides a cost reduction to the plastic industry (and in some cases increases performance as well). For the agro-based industry, this represents an increased value for the agro-based component. Most of the research has concentrated on using a compatibilizer to make the hydrophobe (plastic) mix better with the hydrophil (lignocellulosic). The two components remain as separate phases, but if delimitation and/or void formation can be avoided properties can be improved over those of either phase. These types of materials are usually referred to as natural fibre/thermoplastic blends.

Recent interest in reducing the environmental impact of materials is leading to the development of newer materials or composites that can reduce the stress caused by economic development. In light of petroleum shortages and pressures for decreasing the dependence on petroleum products, there is an increasing interest in maximizing the use of renewable materials. The use of agricultural materials as the source of raw materials for industry not only would mean a switch to renewable sources but could also generate a non-food source of economic development for farming and rural areas.

Several billion kilograms of fillers and reinforcements are used annually in the plastics industry. The use of additives in plastics is likely to grow with the introduction of improved compounding technology and of new coupling agents that permit the use of high filler/reinforcement content (Katz and Milewski, 1987). As suggested by these authors, fillings of up to 75 ppm could be common in the future, a development that could make a tremendous impact in efforts to lower the usage of petroleum-based plastics. It would be particularly beneficial, in terms of the environment but also in socio-economic terms, if a significant percentage of the fillers were to be obtained from renewable agricultural sources. Ideally, of course, an agro-/bio-based renewable polymer reinforced with agro-based fibres would make the most environmental sense.

The primary advantages of using annual growth lignocellulosic fibres as fillers and/or reinforcements in plastics are their low densities, non-abrasive properties, and high filling levels, characteristics that may account for their stiffness and that make them easily recyclable. Unlike brittle fibres, the fibres will not be fractured when processing takes place over sharp curvatures. They are biodegradable, inexpensive and require low energy consumption to produce. Use of the wide variety of fibres that are available throughout the world would generate more rural jobs and give a boost to the non-food agricultural or farm-based economy. As far as industry is concerned, the low cost of the fibres and their higher filling levels, coupled with the advantage of being non-abrasive to the mixing and the moulding equipment are all benefits that are not likely to be ignored by the plastics industry for use in the automotive, building, appliance and other applications.

Prior work on lignocellulosic fibres in thermoplastics has concentrated on wood- based flour or fibres and significant advances have been made by a number of research studies (see Woodhams *et al*., 1984, Kokta *et al*., 1989, Yam *et al*., 1990, Bataille *et al*., 1989). A study of the use of annual-growth lignocellulosic fibres indicates that these fibres have a high potential for use as reinforcing fillers in thermoplastics (Sanadi *et al.,* 1994b). The use of annual-growth agricultural crop fibres such as kenaf has resulted in significant advantages when compared to typical wood based fillers or fibres such as wood flooring, wood fibres and recycled newspaper. Properties of compatibilized PP and kenaf have mechanical properties comparable to those of commercial PP composites (Sanadi *et al*., 1994b)

The costs of natural fibres are, in general, lower than of plastics and consequently high-fibre loading can result in significant material cost savings. The cost of compounding is likely to be much less than for the conventional mineral and inorganic-based composites presently used by plastics industry. Due to the lower specific gravity of the cellulosic-based additives (approximately 1.4 as compared to about 2.5 for mineral-based systems), the weight of the composite is an advantage that may have implications in applications for the automotive and transportation sector. Furthermore, using the same weight of plastic and natural fibre, as for example plastic and glass fibre, the cellulose-based system can produce approximately 20 percent more pieces. Cellulosic fibres are soft and non-abrasive and high filling levels are possible. Reduced equipment abrasion and the subsequent reduction of re-tooling costs through the use of agricultural-based fibres is a factor that definitely will be considered by the plastics industry when evaluating the advantages of natural fibres. It is important to point out that we do not anticipate nor intend the total replacement of conventional based fillers and/or fibres with agricultural based fillers and/or fibres. We do, however, believe that these natural materials will develop their own niche in the plastics filler/fibre market in the future.

The quantities of thermoplastics used in the housing, automotive, packaging and other low-cost, high-volume applications are enormous. Recent interest in reducing the environmental impact of these materials is leading to the development of newer materials or composites that can reduce stress to the environment. In light of petroleum shortages and the mounting pressure on all of us to limit dependence on petroleum products, there is an increasing interest in maximizing the use of renewable materials. The use of agricultural resources as raw materials to industry not only provides a renewable source, but could also generate a non-food source of economic development for farming and rural areas. Appropriate research and development in the area of agricultural-based filler and fibre-filled plastics could lead to new value-added, non-food uses of agricultural materials.

## Fibre Applications: GEOTEXTILES

Vegetable fibres can be grouped into three classes, namely bast fibres, leaf fibres and seed or fruit fibres. Bast fibres are extracted from stems of plants, and the other two groups are self-explanatory. In terms of quantity of production, each of the bast fibres such as jute and flax, leaf fibres such as sisal and curaua and seed or fruit fibres such as cotton and coir are cultivated in the amount of more than 100 000 metric tonnes per annum, though production of cotton is far greater than any of these fibres. The bast fibres are much softer than the leaf fibres and hence enjoy a more diversified end use. Flax, hemp and ramie are used in twines, canvases, fishnets, fire hoses etc., whereas the leaf fibres are employed as cordage material or even as mats. Coir has end uses similar to those of leaf fibres, whereas cotton is used mostly in apparel and jute in sacking and carpeting. All these materials could be cultivated more intensively as new suitable end uses are discovered especially for geotextile applications. A fibre material would be suitable for geotextile if: i) it has reasonably good mechanical properties; ii) it is reasonably resistant to biodegradation; and iii) it has higher lignin content, e.g. coir or African palm.

The bast fibres – namely flax, hemp, kenaf and ramie – have very high tenacity values (between 45-66 cN/tex) and low extension at break (1.6 - 3.8 per cent). Jute is weaker than the fibres named (Ca. 30 cN/tex) but extends almost as much at break. In tenacity, the leaf fibres are slightly stronger than jute but weaker than the three bast fibres such as flax, hemp and kenaf; in extension at break, they behave in a similar fashion to the bast fibres. The tenacity of coir fibres, on the other hand, is very low (15 cN/tex) but elongation at break is much higher (around 40 percent). Therefore, these fibres could be used as geotextiles, although sisal fibres compared favourable against other commercially produced leaf fibres. In fact, trials with sisal fibres for erosion control have been reported to be encouraging (Batra, 1985).

The growth of micro-organisms on vegetable fibres depends on their chemical composition. The lignin content plays an important role herein. In this respect alone, coir fibre, with a lignin content of approximately 35 percent, stands out as extremely resistant followed by jute (circa 12 percent) and leaf fibres (approximately 10 percent). The other bast fibres contain much lower quantities of lignin (0.6 to 3.3 percent). Jute, coir and leaf fibres also appear to have a distinct advantage over the other bast fibres even in terms of their lignin hemicellulose ratio. In terms of the crystallinity of the cellulose content, which also influences its biodegradability (Batra, 1985), comparative results are not available for these different fibres although it is known that it is quite high for the leaf fibres and low for a seed fibre such as coir.

It does appear from the preceding short discussion that in addition to exploring the applicability of jute and coir fibres for geotextile end uses, leaf fibres should also be considered as a potential raw material for geotextiles. This has already been done for sisal fibres and the results were outstanding. This last research study was funded by the CFC and was part of a proposal made by the ICB FAO-IGGHF.

At present, the use of natural fibre geotextiles is limited to control of hill-slope erosion and erosion in the perimeter of slow-flowing minor water courses such as small rivers and ditches. The United States’ consumption of 53 mm2 for erosion control relates to synthetic products applied to both hill-slope erosion control and erosion control of armoured revetments applied to coastal sites as well as to substantial water courses such as large rivers and navigable waterways.

Hill-slope erosion control can be achieved in many different ways, including through land management, vegetation growth and the application of a protective covering. The protective covering can be applied using a variety of techniques such as mulching, sprayed emulsions and sheet-like products, all of which fall under the general category of rolled erosion control products.

It is widely accepted that the establishment of permanent vegetative cover for bare soil is the most efficient and aesthetically pleasing form of long-term erosion control. However, in the short term, immediately after seeding and until vegetation becomes established, soil remains vulnerable to erosion. This problem has led to the creation of an entire industry involved in the manufacture of rolled erosion control products (RECP) that are used to mitigate short-term erosion and in some cases to enhance the long-term erosion control performance of established vegetative cover. It is this latter group which is of interest and which has been sub-classified by the International Erosion Control Association.

RECP covers a diverse range of product structures, including erosion control nets, open-weave geotextiles, erosion control blankets or geosynthetic mats, and an equally diverse range of materials, including, wood excelsior, straw, jute, coir, polyolefins, PVC and nylon. This wide spectrum of structures and materials has led to a confusing array of products that have now been classified by product type and application. Although not yet universally adopted, a five- product classification system, consisting of erosion control nets (ECN), erosion control meshes (ECM), erosion control blankets (ECB), turf reinforcing mats, or matrices (TRM), and erosion control re-vegetation mats (ECRM) is now being applied in the United States.

Geotextiles are used in a wide range of areas. Following are some important application areas where treated–untreated, blended–non-blended, natural and synthetic geotextiles are used. They may be woven, non-woven, knitted, netted, corded, composite and sandwiched. But the application of geotextiles is location- specific so in addition to the intrinsic characteristics of geotextiles, their identification and application depend among other things on soil type, soil composition, moisture content, liquid limits, plasticity index, bulk density, soil pH, iron/calcium content, clay/silt and sand composition, land sloping and hydraulic action.

There are two principal ways in which the consumption of natural fibre geotextiles could be increased. One is to develop new products and applications, or to develop a specific product for a specific application, in other words to develop a niche product. The second is to re-conquer and expand existing markets, primarily through erosion control applications, thereby improving the quality of existing products and providing a stable supply and price structure; this has been done for fibres such as sisal, jute and coir.

The principal market is that of what is probably the single largest application, soil stabilisation, mainly related to roads and highways. The second niche market is in railways, used in a similar way in that geotextiles are applied at the interface of the formation soil and the track bed to minimize pumping of soil fines into the granular material of the track bed. In Brazil alone, it is possible to estimate a potential market of 100 million m per year, mainly for new railroad tracks under construction.

The other strategy used to enhance the natural fibre geotextile market is the LCA (Life Cycle Assessment); this could be very important both in assessing man-made fibres versus the natural fibres, including the major commercial fibres and the lesser known ones such as curaua, not to mention other inexpensive fibres, such as African palm, kenaf and coir. Certification is another tool to be considered, with the principal parameters including quality, environment, health and safety, hygiene and finally sustainability. Several examples of certification labels can be listed, including: PEFC, OCCP, Sustainable forestry initiative, FSC, Rainforest alliance, WWF, Bio and Fairtrade.

Existing natural fibre geotextiles do not compete easily with synthetic products in mainstream applications due to their poor durability, but this can be an advantage in case of applications where biodegradation is an important and desirable factor.

In addition to the need to make them economically and technically viable, natural fibre products will have to comply with national standards that specify the properties of geotextiles required for various applications. Therefore, blends of man-made and natural, and also 3D-formulated natural geotextiles are used. Blends of natural and man-made fibres are more important today than ever before and their number is virtually limitless. The three-dimensional geotextile matrixes are designed especially for erosion control applications in which maximum strength and durability are required. UV-stabilized monofilament yarns woven into a dimensionally stable pyramid such as openings, has excellent tensile strength as an erosion matrix along with a high coefficient of friction and superior interface shear resistance. It provides superior protection and better long-term performance to that offered by 3D Turf Reinforcement Mats (TRM's), and is an excellent alternative to hard-armour systems. There is little question at this point but that national standards worldwide must accept the natural fibres as an appropriate raw material for geotextiles products.

## Biocomposites

There is a growing movement of scientists and engineers dedicated to minimizing the environmental impact of polymer composite production, people who believe that environmental footprints must be diminished at every stage of the life cycle of the polymer composite. Using natural fibres with polymers based on renewable resources will allow many environmental issues to be solved. By embedding biofibres with renewable resource-based biopolymers such as cellulosic plastics, polylactides, starch plastics, polyhydroxyalkanoates (bacterial polyesters) and soy-based plastics, the so-called “green” biocomposites could soon be the wave of the future.

Nowadays, due to their many advantages (such as reduced weight and lower manufacturing costs) biocomposites are the subject of extensive research, specifically in the construction and building industry. Currently, not only builders but also many homeowners are interested in using biocomposites for things like decks, fencing, and so on.

Biocomposites may be classified, with respect to their applications in the building industry into two main groups: structural and non-structural biocomposites (Rowell, 1995). Portland cement is the most widely used manufactured material (Mehta and Monterio, 1993), but the fact is that plain concrete, mortars, and cement pastes are brittle, possess low tensile strength, and exhibit low tensile strains prior to failure. These shortcomings have been traditionally overcome by embedding some other material with greater tensile strength within the cement-based material. Among the different types of fibres used in cement-based composites, natural fibres offer distinct advantages such as availability, renewability, low cost, and modern manufacturing technologies.

One promising and often-used natural fibre for this purpose is wood pulp. Wood pulp fibre-cement composites offer numerous advantages when compared to both non-fibre-reinforced cement materials as well as other fibre-reinforced, cement-based materials. Fibre-cement composites exhibit improved toughness, ductility, flexural capacity and crack resistance as compared to non-fibre , cement-based materials. Pulp fibre is a unique reinforcing material as it is nonhazardous, renewable, and readily available at a relatively low cost when compared to other commercially available fibres (MacVicar *et al*. 1999). As a result of these various advantages, pulp fibre-cement composites have found practical applications in the commercial market as a replacement for hazardous asbestos fibres. Today, pulp fibre-cement composites can be found in products such as extruded non-pressure pipes and non-structural building materials, mainly thin-sheet products. Perhaps the most widely known are the fibre-cement siding materials that some have dubbed “tomorrow’s growth product” (Kurpiel 1998). As of the late 1990s, fibre-cement makes up 7–10 percent of the North American sidings market (Kurpiel, 1997), with some analysts projecting a 25 percent growth rate per year over the next few years (Hillman, 2003). Other currently available commercial fibre-cement products include cladding (which can replicate brick or stucco), architectural elements, shakes and shingles, backer board and underlayment, as well as fascia and soffit panels.

Since ancient times, natural fibres have been used to reinforce brittle materials. For example, thousands of years ago, the Egyptians began using straw and horsehair to reinforce and improve the properties of mud bricks (Mehta and Monterio, 1993). In more recent times, the large-scale commercial use of asbestos fibres in a cement paste matrix began with the invention of the Hatschek process in 1898. However, primarily due to health hazards associated with asbestos fibres, alternate fibre types were developed and introduced throughout the 1960s and 1970s. Among the most promising replacements for asbestos are natural fibres. Depending on their application, fibre-cement materials can offer a variety of advantages over traditional construction materials: i) as compared to wood, fibre-cement products offer improved dimensional stability and resistance to moisture, decay and fire; ii) as compared to masonry, fibre-cement products facilitate faster, lower-cost, lightweight construction; and iii) as compared to cement-based materials without fibres, fibre-cement products may offer improved toughness, ductility, and flexural capacity, as well as crack resistance and “nailability”. A project was funded by CFC (Common Fund for Commodities) to use sisal as a replacement for asbestos in roof applications.

The primary disadvantage of natural fibres in cement-based composites is their vulnerability to decomposition in the alkaline environment present in Portland cement (Balaguru and Shah, 1992). Generally, natural fibres used in cement-based matrices can be divided into two categories: unprocessed natural fibres and processed natural fibres. The unprocessed natural fibres are available in many different countries and represent a continuously renewable resource. These fibres are inexpensive and require low energy consumption when produced and prepared with locally-available manpower and technology. Such fibres are used in the manufacturing of low-fibre-content composites and occasionally have been used in manufacturing thin-sheet high-fibre-content composites. Generally, these fibres are used in low-cost housing projects in less-developed countries. On the other hand, processed natural fibres, such as kraft pulp fibres, which require sophisticated manufacturing processes to extract the fibres, have been used in commercial production since the 1960s for the manufacturing of thin-sheet, fibre-reinforced cement products (Bentur and Mindess, 1993). Initially, these were used with asbestos fibres, but since the mid-1980s they have been used in all applications as the sole reinforcer in place of asbestos fibres. Fibre-cement composite products for residential housing generally have been limited to exterior applications such as siding, and roofing. Their exterior use has been limited in the industry due to degradation from ambient wetting and drying. In fact, these components must have regular painting maintenance to avoid moisture problems. Furthermore, the applications of these composite products are non-structural (i.e., non-load-bearing) in nature.

Possibilities for extruded fibre-cement composites for residential applications include structural sections, trusses, joists, gutters, and piping. In interiors, composites may be used to manufacture cabinets, panelling, shelving, doors, mouldings, railings, and stairs. New composite cast-in-place procedures also have the capability to expand the applications of these composites in the housing sector. In this area, research goals include developing techniques (e.g., fibre treatment, mixing methods) to achieve uniform fibre distribution at high-fibre contents, as well as rheological characterization of large-scale mixes. Establishing the technology for casting-place fibre-cement composites will allow for the construction of large-scale structural elements such as driveways, sidewalks, and foundations with pulp fibre reinforcement. Similarly, technological improvements that allow cast-in-place production also pave the way for modular construction using pre-cast elements such as fibre-cement panels. To reduce transportation costs and energy requirements, reductions in the self-weight of fibre cement composites are an important research area. In addition, the possibility of pulp fibre reinforcement of existing lightweight building materials such as blocks and panels, similar to aerated autoclaved concrete members, should be investigated. Fibres will make these materials more robust and crack-resistant during transport and construction. Because cement-based materials are well-known insulators, another avenue for further research and product development is the strategic use of fibre-cement composites for sound and heat insulation. Such products might be composed wholly of fibre-cement (aerated) or as just a single component in an insulating panel.

## Structural Application

A structural biocomposite can be defined as one that is needed to carry a load in use. For instance, in the building industry, load-bearing walls, stairs, roof systems and sub-flooring are examples of structural biocomposites. Structural biocomposites can range broadly in performance, from high performance to low performance materials.

Bio-based composite materials have been tested for suitability in roof structures (Dweib *et al.,* 2006). Structural beams have been designed, manufactured and tested, yielding good results. Soy oil-based resin and cellulose fibres, in the form of paper sheets made from recycled cardboard boxes, may be used for the manufacture of such composite structures.

The SIP forms, which are utilized to span the distance between bridge girders that are made from biocomposites, have many benefits in comparison to steel forms. Biocomposite-based SIP forms are porous or breathable. This allows water to evaporate through the form and to avoid any rebar corrosion. The form is also biodegradable; a bio-based form has the potential to break down in the future, allowing underside inspection of the bridge deck. In addition, the form is lighter when compared to a steel form, allowing faster and less expensive installations.

## Nonstructural Applications

A non-structural biocomposite can be defined as one that need not carry a load during service. Materials such as thermoplastics, wood particles, and textiles are used to make this kind of biocomposites. Non-structural biocomposites are used for products such as ceiling tiles, furniture, windows, doors, and so on.

Wood fibre plastic composites are made in standard lumber profile cross-section dimensions in exterior construction. These bioproducts are utilized as dock surface boards, decks, picnic tables, landscape timbers, and industrial flooring. Many manufacturers recommend that biocomposites require gaps on both edges and ends for their thermal expansion. Furthermore, wood-based bioproducts are gapped for expansion due to moisture absorption.

Biocomposites are utilized for the construction of composite panels. There are three types of panels: fibreboard, particleboard, and mineral-bonded panels. Bagasse fibres are used for particleboards, fibreboards, and composition panel production. Cereal straw is the second most usual agro-based fibre in panel production. The high percentages of silica in cereal straw mean that products made with it are naturally fire-resistant. Also, the low density of straw panels has made them resilient. Results show that houses built with these panels are resistant to earthquake. Straw is also used in particleboards. Rice husks are also fibrous and need little energy input to prepare the husks for use. Rice husks or their ash are used in fibre-cement blocks and other cement products. The presence of rice husks in building products helps to increase acoustic and thermal properties. A stress-skin, panel-type product has been made by using polyurethane or polyester foam in the core and ply-bamboo in the faces (Govindarao, 1980). Figure 3 indicates the performance of cellular biocomposite panels compared with conventional slab and panel systems for commercial and residential construction.

Natural fibre composites can be very cost effective when used for the following applications:

* Building and construction industry: panels for partition and false ceilings, partition boards, walls, floors, windows and door frames, roof tiles, mobile or pre-fabricated buildings that can be used in times of natural calamities such as floods, cyclones, earthquakes, etc.;
* Storage devices: post boxes, grain storage silos, bio-gas containers, etc.;
* Furniture: chairs, tables, showers, bath units, etc.;
* Electrical devices: electrical appliances, pipes, etc.;
* Everyday applications: lampshades, suitcases, helmets, etc.;
* Transportation: automobile and railway coach interiors, boats, etc.; and
* Toys.

The use of natural fibre reinforcement has proved viable in a number of automotive parts. At Fiat, Flax, sisal, and hemp are processed into door cladding, seatback linings, and floor panels. Coconut fibre is used to make seat bottoms, back cushions, and head restraints. Cotton is used to provide soundproofing and wood fibre is used in seatback cushions (Table 3). Acaba is used in under floor body panels. Several other manufacturers are implementing natural ingredients into their cars as well. For example, the BMW Group incorporates a considerable amount of renewable raw materials into its vehicles, including 10 000 tonnes of natural fibres in 2004 alone. At General Motors, a kenaf and flax mixture has gone into the manufacture of package trays and door panel inserts for Saturn L300s and the European-market Opel *Vectra*, while wood fibre is being used in seatbacks for the Cadillac *DeVille* and in the cargo area floor of the GMC *Envoy* and the Chevrolet *TrailBlazer*. Ford mounts Goodyear tires that are made with corn on its fuel-sipping *Fiestas* in Europe. Goodyear has found that its corn-infused tires have lower rolling resistance than traditional tires, so they provide better fuel economy. The sliding door inserts for the Ford *Freestar* are made with wood fibre. Toyota is considering using kenaf to make *Lexus* package shelves, and already has incorporated it into the body structure of Toyota’s *i-foot* and *i-unit* concept vehicle.

**Table 4: Examples of interior and exterior automotive parts produced from natural materials (Mohanty *et al*., 2005)**

|  |  |
| --- | --- |
| **Vehicle part** | **Material used** |
| ***Interior*** | |
| Glove box | Wood/cotton fibres, moulded flax/sisal |
| Door panels | Flax/sisal with thermoset resin |
| Seat coverings | Leather/wool backing |
| Seat surfaces/backrests | Coconut fibre/natural rubber |
| Trunk panel | Cotton fibre |
| Trunk floor | Cotton with PP/PET fibres |
| Insulation | Cotton fibre |
| ***Exterior*** | |
| Floor panels | Flax mat with polypropylene |

In Brazil the average consumption of natural fibre reinforcement in the automotive industry amounts to (Leao, 2010):

* Front door liners [1.2-1.8 kg]
* Rear door liners [0.8-1.5 kg]
* Boot liners [1.5-2.5 kg]
* Parcel shelves [2 kg]
* Seat backs [1.6-2.0 kg]
* Sunroof interior shields [0.4 kg]
* Headrests [2.5 kg]

Overall, the variety of bio-based automotive parts currently in production is astonishing; DaimlerChrysler is the biggest consumer with up to 50 components in its European vehicles being produced from bio-based materials.

Currently, there is a great deal of global research into the insertion of natural fibre composites into the manufacturing process and automakers are producing prototypes that provide an indication of what the future of automobile manufacturing will be like. The reasons for the application of natural fibres in the automotive industry include:

* Low density: which may lead to a weight reduction of 10 to 30%;
* Acceptable mechanical properties, good acoustic properties;
* Favourable processing properties, for instance little wear on tools, etc.;
* Options for new production technologies and materials;
* Favourable accident performance, high stability, less splintering;
* Favourable ecobalance for part production;
* Favourable ecobalance during vehicle operation, due to weight savings;
* Occupational health benefits (compared to glass fibres) during production;
* No off-gassing of toxic compounds (in contrast to phenol resin-bonded wood and recycled cotton fibre parts);
* Reduced fogging behaviour;
* Price advantages regarding both fibres and applied technologies.

## Aerospace Application

Aerospace technology was the first sector to boast a significant range of applications for fibre-reinforced polymers (FRP). Since then, however, these construction materials have also been used for numerous technical applications, especially where high strength and stiffness at low weight is required. The good specific, i.e. weight-related properties, of these materials (unsaturated polyester, polyurethane, phenolic or epoxy resins) are due to the low densities of the applied matrix systems and the presence of embedded fibres (glass, aramid and carbon fibres) that give high strength and stiffness. Furthermore, during production the option of tailoring a composite part to specific needs is done by orientating the reinforcing fibres into the load directions. Thus, the compound, i.e. the material itself, results directly from the manufacturing of the structure.

Over time, a variety of technologies have been developed. With the classic fibre-reinforced polymers, however, there are often considerable problems with respect to re-utilization or recycling after the end of life-times; this is mainly due to the fact that these materials are compounds of miscellaneous fibres and matrices that are generally extremely stable. Increasingly, the once popular solution of simple landfill disposal is no longer an option because of growing sensitivity regarding the environment. The search is on, therefore, for environmentally compatible alternatives, such as recovery of raw materials, CO2-neutral thermal utilisation or – in certain circumstances – biodegradation. Another interesting option may be that of construction materials which are developed from renewable resources; in this case, natural fibres are embedded into so-called biopolymers and used in economically and ecologically acceptable manufacturing technologies.

Due to advantages in weight, mechanical stability and price, interest in the application of natural, fibre-reinforced materials is growing in the aerospace industry in both the United States and Europe. Applications for the use of materials based on thennoplastics are being evaluated for possible approval by the United States Federal Aviation Authority and the United Kingdom Civil Aviation Authority.

## Natural Fibre Nanocomposite Applications

The potential applicability of nanocellulose is extremely broad. Applications of nanocellulose are to be found principally in paper and packaging products, although construction, automotive products and components, furniture, electronics, pharmacy and cosmetics are also being considered. For companies producing electro-acoustic devices, nanocellulose is used as a membrane for high-quality sound. Additionally, nanocellulose is applied in: membranes for combustible cells (hydrogen); additives for high-quality electronic paper (e-paper); ultra-filtrating membranes (water purification); and membranes used to retrieve mineral and oils (Brown

Jr., 1998). A vast variety of other applications also are being researched. The high strength and stiffness, as well as the small dimensions, of nanocellulose may well impart useful properties to composite materials reinforced with these fibres and adapted to a wide range of purposes.

###### Electronic Industry

Diaphragms

Among the various applications studied so far, and one which has already reached the level of practical use, is that of acoustic diaphragms. Nanocellulose has been found to bear two essential properties: high sonic velocity and low dynamic loss. In fact, the sonic velocity of pure film was found to be almost equivalent to those of aluminium and titanium (Iguchi, 2000). Jonas and Farah (1998) stated that SONY® had already begun using nanocellulose in the diaphragms they built into headphones. The diaphragms are produced through dehydration and compressed to a thickness of only 20 microns in a diaphragm die. The advantage of the ultra-thin nanocellulose diaphragm is that it can produce the same sound velocity as an aluminium or titanium diaphragm as well as the warm, delicate sounds that a paper diaphragm provides. Trebles are sparkling clear and bass notes are remarkably deep and rich in headphones with these kinds of diaphragms.

Digital displays

Cellulose has always been the primary medium for displaying information in our society and now efforts are underway to develop dynamic display technology, for example in electronic paper. Nanocellulose is dimensionally stable and has a paper-like appearance which gives it the potentiality of a leading role in the basic structure of electronic paper (Shah and Brown, 2005). Shah and Brown demonstrated this in a display device that has many advantages including reflectivity, flexibility, contrast and biodegradability.

Summarizing, the whole idea is to integrate an electronic die into the nanostructure of the microbial cellulose since, once integrated, a simple pixel can be used to reversibly switch from ON to OFF. The pixel size is controlled by the minimum addressing resolution of back-plane drive circuits. (Shah and Brown, 2005). Other studies (Yano *et al*., 2005) have shown that nanocellulose has extraordinary potential as a reinforcement material in optically-transparent plastics; for instance, as a substrate for bendable displays. According to the authors, the composite remained optically transparent even in the presence of high fibre contents.

Legnani *et al*. (2009) developed biodegradable and biocompatible flexible organic light-emitting diodes (FOLED) based on nanocellulose (NC) membranes as substrates. (Figure 8) Nanocomposite substrates based on nanocellulose (NC) and boehmite-siloxane systems with improved optical transmittance in the visible region were used as flexible substrates for FOLED applications. The nanocomposite formations improve the optical transmittance in visible range. Transmittance of 66 percent at 550 nm was found for the NC-nanocomposite/ITO (Indium Tin Oxide) substrate when compared to the 40 percent value at the same wavelength for the NC/ITO substrate. ITO film was deposited at room temperature onto membranes and glass using rf magnetron sputtering with a rf power of 60 W and at pressure of 1 mtorr in Ar atmosphere.

Other electronic uses

Evans *et al*. (2003) found that nanocellulose catalyzed the deposition of metals within its structure, thus generating a finely divided homogeneous catalyst layer. Experimental data suggested that nanocellulose possessed reducing groups capable of initiating the precipitation of palladium, gold, and silver from an aqueous solution. The structure is thus suitable for the construction of membrane electrode assemblies. Olson *et al*. (2010) show that freeze-dried cellulose nanofibril aerogels can be used as templates for making lightweight porous magnetic aerogels that can be compacted into a stiff, magnetic nanopaper.

###### Pharmaceutical applications

Cellulose has a long history of use by the pharmaceutical industry. The material has excellent compaction properties when blended with other pharmaceutical excipients so that drug-loaded tablets form dense matrices suitable for the oral administration of drugs. Polysaccharides and natural polymers, when built into hydrophilic matrices, remain popular biomaterials for controlled-release dosage forms; use of a hydrophilic polymer matrix is one of the most popular approaches in formulating an extended-release dosage form (Alderman, 1984; Heller, 1987; Longer & Robinson, 1990). This is due to the fact that these formulations are relatively flexible and a well-designed system usually gives reproducible release profiles.

Drug release is the process by which a drug leaves a pharmaceutical product and is subjected to absorption, distribution, metabolism, and excretion (ADME), eventually becoming available for pharmacologic action. Crystalline nanocellulose offers several potential advantages as a drug delivery excipient. Crystalline nanocellulose and other types of cellulose can be used in advanced pelleting systems so that the rate of tablet disintegration and drug release may be controlled by microparticle inclusion, excipient layering or tablet coating (Baumann, *et al.,* 2009; Watanabe *et al.,* 2002).

The very large surface area and negative charge of crystalline nanocellulose suggests that large amounts of drugs might be bound to the surface of this material with the potential for high payloads and optimal dosing control. Other nanocrystalline materials, such as nanocrystalline clays, have been shown to bind and subsequently to release drugs in a controlled manner via ion-exchange mechanisms and not surprisingly these are being researched for use in pharmaceutical formulations (Shaikh *et al*., 2007). The established biocompatibility of cellulose supports the use of nanocellulose for a similar purpose. The abundant surface of hydroxyl groups on crystalline nanocellulose provides a site for the surface modification of the material with a range of chemical groups and by a variety of methods. Surface modification may be used to modulate the loading and release of drugs that would not normally bind to nanocellulose, such as non-ionized or hydrophobic drugs. For example, Lonnberg *et al.* (2008) suggested that poly (caprolactone) chains might be conjugated onto nanocrystalline cellulose for such a purpose. Additionally, since crystalline nanocellulose is a low-cost, readily abundant material from a renewable and sustainable resource, its use provides a substantial environmental advantage compared with other nanomaterials.

###### Biomedical Applications

Nanocellulose increasingly has been called into use as a biomaterial with significant applications in the biomedical industry. Its uses include skin replacements for burns and wounds; drug-releasing systems; blood vessel growth; nerves, gum and dura-mater reconstruction; scaffolds for tissue engineering; stent covering and bone reconstruction (Fontana *et al.,* 1990; Mello *et al*., 2001; Czaja *et al.,* 2007; Negrão *et al*., 2006). Figure 9 shows some applications for nanocellulose within the biomedical field (Leao *et al.* 2011).

Tissue engineering is on the lookout for new materials and devices that could interact positively with biological tissues (Croce *et al*., 2004), either serving as an *in- vitro* basis for cell growth or for rearranging and developing tissue which is about to be implanted. Researchers in this field are also looking for new classes of degradable biopolymers that are biocompatible and that possess activities that are controllable and specific (Madihally and Matthew, 1999); these kinds of biopolymers therefore are more likely to be used as cell scaffolds (Nehrer *et al.,* 1997), or *in vitro* tissue reconstruction.

As described above, a large number of biomaterials have been developed recently. They have all sorts of properties (physical, chemical and mechanical) depending mostly on their final application, be it tissue regeneration, medication holding and releasing, tissue grafting, or scaffolding (Czaja *et al.,* 2007). The scaffold’s success depends greatly on the degree of cellular adhesion and growth onto the surface; in this way, biopolymer’s chemical surface dictates cellular response by interfering in cellular adhesion, proliferation, migration and functioning.

The surface cell interaction is extremely important in implant effectiveness, including the blocking of rejection. Since the interaction is fully understood on a cell level, new biomaterials and products can be easily developed (Kumari *et al.,* 2002). Problems still arise due to some methodological inefficiencies involving cell seeds and sources, scaffolding, ambient, extracellular matrix producing, analysis and appropriate models (Ikada, 2006).

On the other hand, to regenerate tissues, three specific factors have to be taken into consideration: cells, support and growth factors. Cells synthesize the matrix for the new tissues, support is important as it holds and keeps the ambient proper for the growth, while the growth factors facilitate and promote cell regeneration (Ikada, 2006). Material used for implants should not be rejected or cause inflammatory response and thus should be biocompatible. Furthermore, such materials should promote regeneration and, if necessary, be absorbable or biodegradable (Chen and Wu, 2005). Studies on support-cell interactions are crucial to implant viability. Many different cell responses are observed, depending on the material utilized. What is important in adherence to a surface is the cell’s ability to discriminate and adapt (Anselme, 2000). This is crucial as further responses such as cell proliferation, migration and viability depend on this.

Due to the clinical importance of skin lesions, many laboratories have been on the lookout for healing products with benefits including immediate pain relief, close adhesion to the wound bed, and a reduced infection rate. The nanocellulose that has been developed for this purpose has a broad superficial area with significant water-absorption capacity and elasticity. These are the characteristics of an ideal healing bandage. Additionally, such a bandage allows no microbial activity. Nanocellulose mats are very effective in promoting autolytic debridement, reducing pain, and accelerating granulation, all of which are important for proper wound healing. These nanobiocellulose membranes can be created in any shape and size, which is beneficial for the treatment of large and difficult-to-cover areas of the body.

Barud (2009) has created a biological membrane with bacterial cellulose and a standardized extract of propolis. Propolis has many biological properties, including anti-microbial and anti-inflammatory activities. All the above-mentioned qualities make the membrane an effective treatment for burns and chronic wounds.

Odontology, too, is currently facing the challenge of where to find the ideal materials to replace the bones in several procedures, such as those concerning bone malformation, maxillary and facial deformities. The biggest challenge is the loss of alveolar bone. Nanocellulose has suitable porosity which makes the mat an infection barrier, prevents loss of fluids, has a painkiller effect, allows medicines to be easily applied and absorbs the purulent fluids during all inflammatory stages, expelling them later in a controlled and painless manner (Czaja *et al.,* 2006).

Polyvinyl alcohol (PVA) is a hydrophilic, biocompatible polymer with various characteristics desired for biomedical applications. PVA can be transformed into a solid hydrogel with good mechanical properties by physical crosslinking, using freeze-thaw cycles. Hydrophilic nanocellulose fibres of an average diameter of 50 nm are used in combination with PVA to form biocompatible nanocomposites. According to Millon and Wan (2006), the resulting nanocomposites possess a broad range of mechanical properties and can be produced with mechanical properties similar to that of cardiovascular tissues, such as aorta and heart valve leaflets. Studies indicate that the stress-strain properties for porcine aorta are matched by at least one type of PVA-nanocellulose nanocomposite in both the circumferential and the axial tissue directions. A PVA-nanocellulose nanocomposite with properties similar to heart valve tissue also has been developed. The relaxation properties of all samples, which are important for cardiovascular applications, were also studied and found to relax at a faster rate and to produce a lower residual stress than the tissues they might replace. This makes the new PVA–nanocellulose composite a promising material for cardiovascular soft tissue replacement applications.

According to Cai and Kim (2010), there are three different methods that can be used to prepare a nanocellulose/PEG composite. In the first method, PEG was incorporated into nanocellulose hydrogels by adding a PEG solution to the culture medium for gluconacetobacter xylinus. In the second method, suspensions of microbial cellulose nanofibres are mixed with PEG solution with mechanical stirring followed by a freezing-thawing process. The composite is a hydrogel and can be used for soft tissue replacement devices. In the third method, a previously produced nanocellulose hydrogel was soaked with PEG solution, allowing the PEG molecules to penetrate the nanocellulose (Seves *et al.* 2001).

The third method seems the most simple and effective. It has also been used to prepare other nanocellulose-based composites. For instance, nanocellulose is soaked in hydroxyapatite to develop a composite scaffold for bone regeneration (Wan *et al*. 2006). Nanocellulose also has been augmented by immersion in solutions of polyacrylamide and gelatin, yielding hydrogels with improved toughness (Yasuda *et al*. 2005). Similarly, immersion of nanocellulose into poly (vinyl alcohol) has yielded hydrogels possessing a wide range of mechanical properties that are of interest for cardiovascular implants (Millon and Wan, 2006). In this latter study, the authors reported on the third method. SEM images showed that PEG molecules were not only coated on the surface of the nanocellulose fibres but also had penetrated into the nanocellulose fibre networks. The prepared scaffold has a much-interconnected porous network structure and a large aspect surface. The TGA results demonstrated the material’s improved thermal stability. Tensile test results indicated that Young’s modulus and tensile strength tended to decrease while the elongation at break showed a slight increase. It showed much better biocompatibility than pure nanocellulose. Thus, the prepared nanocellulose/PEG composite scaffolds are suitable for cell adhesion or attachment, suggesting these scaffolds can be used for wound dressing or tissue-engineering applications.

### In the area of ophthalmology, Huia et al. (2009) explored the potentiality of nanocellulose biomaterial when applied as a scaffold for tissue engineering of the cornea. They studied the growth of human corneal stromal cells on nanocellulose and, after verification though use of the laser scanning confocal microscope, determined that it is suitable as a scaffold for tissue engineering of an artificial cornea. The surface of nanocellulose is lumpy with rills. In Figure 11A and B, the red regions are corneal stromal cells seen after immunofluorescence staining Protocol with Vim and the blue region is the nanocellulose scaffold. It can be seen clearly that the corneal stromal cells grew directly into the scaffold.

In otorhinolaryngology, surgery of the lateral wall of the nose is a common ENT procedure and is recommended for resection of soft lush, removal of tumours or to promote aeration of the sinuses. The evolution of surgical techniques has provided increased safety for patients, drastically reducing complications and postoperative morbidity. Nasal bleeding, surgical wound infections, local pain and adhesions are the major complicating factors related to nasal surgery. Several types of materials have been developed in order to prevent these complications. Nasal packing has been used in these post-surgical procedures and although highly effective in preventing bleeding, removal causes great discomfort to the patient. Moreover, packing has been associated with serious systemic infections.

The use of a material that, in addition to preventing bleeding, could provide more rapid healing (without the formation of crusts) and prevent infection without the need for removal would be of great aid in the postoperative phase to patients who have undergone resection of the lower nasal concha and other nasal surgeries. In 1984, microbiologist Louis Farah Fernando Xavier was able, through the fermentation of bacteria of the *acetobacter* genus, to produce bacterial cellulose. After processing, the film resulting from this synthesis is endowed with selective permeability, allowing the passage of water vapour but preventing the passage of microorganisms. It is semi-transparent, homogeneous, with an average thickness of 0.05 mm and visually very similar to human skin. Schumann *et al.* (2009) studied the artificial vascular implants of nanocellulose in two separate studies. In a first microsurgical study, nanocellulose implants were attached to an artificial defect of the carotid artery of rats for a period of one year and long-term results showed the incorporation of the nanocellulose though the formation of neointima and the ingrowth of active fibroblasts. In a second study, grafts were used to replace the carotid arteries of pigs. After three months, these grafts were removed and analyzed both macroscopically and microscopically. Seven grafts (87.5 percent of the total) were clear whereas one graft was found to be occluded. These data indicate that the innovative nanocellulose engineering technique results in the production of stable vascular conduits; they confirm that this is a highly attractive approach to *in vivo* tissue-engineered blood vessels as part of programs in cardiovascular surgery.

Another use of nanocellulose is for nasal reconstruction. The desire for an ideal nose shape has always been a human longing. The nose, centrally located in the face, is more susceptible than other parts of the face to traumas, deformities and stigma leading to problems of socialization. Despite the fact that its principal function is breathing, the nose has an important aesthetic function, highlighting the face’s genetics. Amorim *et al*. (2009) evaluated the tissue response to the presence of nanocellulose in the nose bone. This study used 22 rabbits; in 20, a cellulose blanket was implanted in the nasal dorsum, while the other two were kept as a control group. After three months, and again after six months, the back bone was extirpated for further histopathological study in which the parameters used included blood vessel clogging, inflammation intensity and the presence of purulent fluids. Inflammation was found to be stable, a factor probably due to the surgical procedure itself and not to the cellulosic blanket. There was no statistical significance for the other parameters. The nanocellulosic blanket showed good biocompatibility and did not change over time, thus proving itself to be an excellent material for elevation of the nose bone.

###### Veterinary

Hart *et al.* (2002) studied the pellicle and its ability to promote fibroblast migration and cellular proliferation in diabetic rats. The treatment accelerated the wound healing for the diabetic rats, and improved their histological outcome. The diabetic rat is a recognized model for chronic wounds, as the latter share some features with the chronic human wound and thus were suitable for predicting applicability in humans.

Helenius *et al.* (2006) were the first to systematically study the *in vivo* biocompatibility of nanocellulose. A nanocellulose membrane was implanted into the subcutaneous space of rats for one, four and twelve weeks. The implants were evaluated in terms of chronic inflammation, foreign body responses, cell ingrowth and angiogenesis, using histology, immunohistochemistry, and electron microscopy. There were no macroscopic signs of inflammation around the implants (redness, edema or exudates) (Figure 14). There were also no microscopic signs of inflammation (i.e., a high number of small cells) around the implants or the blood vessels). No fibrotic capsule or giant cells were present. Fibroblasts were able to infiltrate the nanocellulose (Figure 15), which was well integrated into the host tissue and did not elicit any chronic inflammatory reactions; the biocompatibility of nanocellulose was thereby established and it was proved that the material has the potential to be used as a scaffold in tissue engineering.

Helenius *et al*. (2006) added further to our knowledge of biomaterial and its ability to interact with a living cell. In this study, membranes of nanocellulose had been implanted into rats and the biocompatibility was evaluated *in vivo*. Implants did not cause foreign body reactions, fibrosis or encapsulation, and the rat’s conjunctive tissues were well-integrated with the nanocellulose. Some weeks after the implantation, the fibroblasts were fully integrated into the cellulosic structure and had begun to synthesize collagen. These studies also showed that density influences both morphology and cell penetration: as density increases, cell migration slows. It was observed, in fact, that nucleus morphology depends on the direction taken by the cellulosic nanofibers. Blood flow was also observed.

Silva (2009) evaluated the biological behaviour of synthetic hydroxyapatite (HAP-91) when implanted in dental cavities and covered by nanocellulose. Membranes were shaped into triangles that fully covered the cavities, thereby avoiding contact between hydroxyapatite and the oral cavity (a source of contaminants, figure 16). Silva found that nanocellulose associated with HAP promoted faster bone regeneration when compared with the control group eight days after procedure and, again, after a period of 30 days. After 50 days the tissues appeared identical.

Costa e Souza (2005) studied skin healing in swine that underwent thermal abrasion, (with metal temperatures at 100 °C). Comparing Bionext® to the daily healing bandage, the healing process was the same in all the animals; in other words, no differences were seen between the daily bandage and the cellulose pellicle (Bionext®).

For dogs whose peritoneum had been replaced, it was observed that 45 days after the implant, fibroblasts and blood vessels numbers had increased. After 90 days, collagen and fibroblasts had penetrated into the nanocellulose and 180 days after implantation the nanocellulose had formed a net along the conjunctive tissue, with littleevidence of neovascularisation (Nemetz *et al,* 2001).

###### Dental

Nanocellulose also has been tested in dental tissue regeneration. Microbial cellulose produced with the glucanacetobacter xylinus strain has been seen to be used successfully to regenerate dental tissues in humans. The nanocellulose products Gengiflex® and Gore-Tex® have intended applications within the dental industry. They were developed to aid periodontal tissue recovery. Novaes Jr. and Novaes, (1997) provided a description of a complete restoration of an osseus defect around an IMZ implant in association with a Gengiflex® therapy. The benefits included the re-establishment of both aesthetics and function (of the mouth) and the need for a lower number of surgical steps. The bandage, called Gengiflex®, consists of two layers: the inner layer is composed of microbial cellulose, which offers rigidity to the membrane, and the outer alkali-cellulose layer is chemically modified (Novaes Jr. and Novaes, 1992). Salata *et al.* (1995) compared the biological performance of Gengiflex® and Gore-Tex® membranes using the *in-vivo*,non-healing, bone-defect model proposed by Dahlin *et al.* (1988).

The study showed that Gore-Tex® membranes (a composite with polytetrafluoroethylene, urethane and nylon) were associated with significantly less inflammation and that both membranes (Gore-Tex® and Gengiflex®) promoted the same amount of bone formation during the same period of time. When compared to the control sites, a greater amount of bone formation was present in bone defects protected by either Gore-Tex® or microbial cellulose membrane. Gore-Tex® is better tolerated by tissues than Gengiflex®. Recently, a similar study, Macedo *et al.* (2004)also compared bacterial cellulose and polytetrafluoroethylene (PTFE) as physical barriers used to treat bone defects in guided tissue regeneration. In this study, two osseous defects (8 mm in diameter) were performed in each hind foot of four adult rabbits, using surgical burs with constant sterile saline solution irrigation. The effects obtained on the right hind-feet were protected with PTFE barriers, while Gengiflex® membranes were used over wounds created in the left hind feet. After three months, the histological evaluation of the treatments revealed that the defects covered with PTFE barriers were completely repaired with bone tissue, whereas incomplete lamellar bone formation was detected in defects treated with Gengiflex® membranes, thereby resulting in voids and lack of continuity in bone deposition. Recent studies by Leao *et al*. at UNESP/Botucatu (Brazil) have looked at a replacement for bacterial cellulose made of vegetal cellulose from pineapple and sisal.

With its various characteristics – its nanofibre size and distribution, its mechanical properties, compatibility and ability to mould – nanocellulose has been used to create a unique biomaterial that has become indispensable in the health area. The nanocellulose composite scaffolds are biocompatible and provoke so little rejection with cellular contact and with blood contact cell interaction that they promise to be a biomaterial that may well be suitable for cell adhesion and/or attachment; in other words, the research suggests that these scaffolds can be used successfully for wound-dressing or tissue-engineering scaffolds.

###### Full plant utilization

In 1997, international concerns about global warming caused by excessive emissions of greenhouse gases led to the adoption of the Kyoto Protocol to the United Nations Framework Convention on Climate Change (UNFCCC). The Protocol commits industrialized countries, known as Annex I countries, to reduce greenhouse gas emissions during the first commitment period between 2008 and 2012. As the first year of the first commitment period came to an end, discussions for the post-Kyoto climate change agreements were held (in December 2008) in Poznan, Poland. Several industrialized countries pledged to reduce carbon emissions by up to 80 percent. In addition to increasing energy efficiency and reliance on renewable energy sources such as wind and solar power, the reduction of emissions from deforestation and forest degradation (REDD) is also likely to be an important mitigation option in the post-Kyoto Protocol period; it should be remembered, in fact, that deforestation and forest degradation are responsible for the release of about 1.5–2.2 Gt C yr−1, or approximately 25 percent of annual global emissions.

In addition to increasing carbon emissions, deforestation and forest degradation significantly reduce the availability of woody biomass on which approximately 2.5–2.7 billion people depend for daily cooking fuel. Given the widespread dependency on wood for energy and the importance of forests to the mitigation of climate change, there is a strong need to assess future availability while developing a plan that will take us toward the sustainable use and management of forests. Canadell and Raupach (2008) proposed four strategies for managing forests for climate change mitigation. One is to expand the use of woody biomass to replace the use of fossil fuels. Smeets and Faaij (2007) provided an assessment of wood bioenergy potentials on a global scale, concluding that there is high potential for amassing woody biomass from forests. Kinoshita *et al*. (2009) evaluated the utilization of thinned wood for bioenergy in Japan and concluded that bioenergy will be increasingly important as a substitute for the use of oil.

The utilization of woody biomass for power generation also has a potential role in global warming mitigation because of the low emissions of greenhouse gases when compared with the use of oil or coal. To avoid power shortages such as those which occurred in 2001 in Brazil, the Brazilian government has launched incentive programs to encourage the utilization of biomass (including woody biomass) as bioenergy and biofuel (bioethanol) and recently several companies began looking at the possibilities of using excess biomass for second-generation ethanol and biomethanol. All these studies show the importance of woody biomass in climate change mitigation and therefore in sustainable development.

With concerns mounting about global warming and about the dwindling supplies of expensive fossil fuels , many countries are actively seeking a new, better and more-sustainable energy structure. Virtually every Western country, and many Asian and South American countries as well, are investing vast amounts of money in research and development and in building biorefineries to produce biofuels and bioelectricity from a variety of renewable natural raw materials. For example, under the United States’ Energy Policy Act of 2005, the Department of Energy was called upon to look into displacing conventional fuel with biofuels by a minimum of 15 percent by 2017 and more than 30 percent by 2030. This means that biofuel production must ramp up to about 60 billion gallons (227 billion litres) per year by 2030. And this figure refers to the United States alone.

Some natural raw materials such as grains (primarily corn), sugarcane and sugar beets can and are being used for bioethanol fuel production. However, the fermentation processes used to convert these raw materials to ethanol require large amounts of steam and electric power that, paradoxically, often are produced by using fossil fuels. And it should be remembered that utilizing grains for biofuels can impact negatively on food prices since grains area also used in human food as well as livestock feed. Furthermore, there may be limitations on the amount of corn grain ethanol that can be produced in the United States, with some predicting a maximum of about 15 billion gallons (57 billion litres) per year.

Renewable biomass resources such as wood waste, agricultural residues and biomass crops are the most plentiful renewable energy resource in the world, a largely untapped resource that can be converted into clean fuels such as biodiesel, biomethanol, bioethanol, biobutanol (Fischer-Tropsch) and into clean power products currently supplied by fossil fuels. Many of these sources are still commonly considered as nothing more than waste products. But there are two platforms that are being developed for converting biomass to biofuel and creating bioelectricity in biorefineries:

- A *thermochemical platform*that uses low- or medium-temperature gasification, or higher-temperature pyrolysis, to create a high hydrogen-content synthetic gas (syngas) that can be employed for electricity generation using gas turbines or, as an alternative, can be catalytically converted into liquid biofuels.

- A *biochemical platform*that uses steam, diluted acid, concentrated acid and/or enzyme hydrolysis to convert (that is, depolymerize) the hemicellulose and cellulose of biomass into simpler pentoses (C5 sugars) and glucose (C6 sugars), a process that is also called saccarification. These sugars are then fermented and distilled into alcohol (mainly ethanol).

Most of the initiatives for converting biomass into biofuels are looking into the possibility of utilizing highly efficient, non-wood plants (those with a high photosynthesis rate) such as switch grass, miscanthus (elephant grass), sisal, *arundo donax* (giant reed), cereal straws, corn and other stalks, and other agricultural crops and residuals. Regardless of the platform, converting a non-wood, fibre-based biomass to a biofuel or biopower-biorefinery project generally involves the harvesting, baling, transportation, long term storage and preparation of very large volumes of biomass. The harvesting of many agricultural residues and biomass crops typically requires from six to eight weeks; these products then need to be stored for an entire year to feed the biofuel or biopower facility. With the new trend, worldwide, of decarb products, the natural fibres are an excellent alternative as a sustainable source of biopolynmers and bioproducts.

**References**

**Alderman, D.A**.**A**. 1984. Review of cellulose ethers in hydrophilic matrices for oral controlled release dosage forms. *International Journal of Pharmaceutical Technology and Product Manufacture*, vol. 5, pp. 1-9.

**Amar K., Manjusri, M. & Lawrence, T.D**. 2005. Natural Fibres, Biopolymers, and Bio-composites, *CRC Press, Tailor & Francis*.

**Amorim, W.L., Costa, H.O., Souza, F.C., Castro M.G.& Silva, L**. 2009. Experimental study of the tissue reaction caused by the presence of cellulose produced by Acetobacter xylinum in the nasal dorsum of rabbits, *Brazilian Journal of Otorhinolaryngology*, vol. 75, no. 2, pp. 200-207.

**Anselme, K**. 2000. Osteoblast adhesion on biomaterials, *Biomaterials*, vol. 21, no. 7, pp. 667-681.

**Balaguru, P.N & Shah, S.P**. 1992. *Fibre Reinforced Cement Composites*, New York, McGraw Hill.

**Barud, H.S**. 2009. Development and evaluation of Biocure obtained from bacterial cellulose and standardized extract of propolis (EPP-AF) for the treatment of burns and / or skin lesions, Brazil, São Paulo Research Foundation *–* FAPESP,.

**Bataille, P., Ricard, L. & Sappicha, S.** 1989. Effect of Cellulose in Polypropylene Composites, *Polymer Composites*, vol. 10, pp. 103.

**Batra, S.K**. 1985. Long vegetable fibres. *In* M. Lewin & E. Pearce, eds. *Handbook of Fibre Science and Technology Fibre Chemistry*. New York. Marcel Dekker Inc.

**Baumann, M.D., Kang, C.E., Stanwick, J.C**., **Wang, Y., Kim, H., Lapitsky,Y. & Shoichet, M. S.** 2009. An injectable drug delivery platform for sustained combination therapy, *Journal of Controlled Release*, vol. 138, no. 3, pp. 205–213.

**Bentur A. & Mindess S**. 1993. Effect of drying and wetting cycles on length and strength changes of wood fibre reinforced cement. *Durability of Building Materials*, vol. 2, pp. 37-43.

**Brown, R.M.** 1998. Microbial Cellulose: a new resource for wood, paper, textiles, food and specialty products. *Position Paper* (Available at www.botany.utexas.edu/facstaff/facpages/mbrown/position1.htm).

**Burgueño, R., Quagliata, M.J., Mehta, G.M., Mohanty, A.K., Misra, M. & Drzal, L.T**. 2005. Sustainable Cellular Biocomposites from Natural Fibres and Unsaturated Polyester Resin for Housing Panel Applications, *Journal of Polymers and the Environment*, vol. 13, no. 2, pp. 139-149.

**Cai, Z. & Kim, J**. 2010. Bacterial cellulose/poly(ethylene glycol) composite: characterization and first evaluation of biocompatibility. *Cellulose*, vol. 17, no. 1, pp. 83-91.

**Chen, G.Q. & Wu,Q**. 2005. The application of polyhydroxyalkanoates as tissue engineering materials, *Biomaterials*, vol. 26, no. 33, pp. 6565-6578.

**Costa, H.O.& de Souza, F.C.** 2005. Evaluation of the tissue regeneration of the burned pig´s skin followed by BiotissueTM grafting”, *Acta ORL/Técnicas em Otorrinolaringologia*, vol. 23, no. 4.

**Croce, M.A., Silvestri, C., Guerra, D., Carnevali, E., Boraldi, F., Tiozzo, R.& Parma,B.** 2004 Adhesion and proliferation of human dermal fibroblasts on collagen matrix, *Journal of Biomaterials Applications*, vol. 18, no. 3, pp. 209-222.

**Czaja, W., Krystynowicz, A., Bielecki, S. & Brown, R.M. Jr. 2006.** Microbial cellulose—the natural power to heal wounds. *Biomaterials*,vol. 27, no. 2, pp. 145-151.

**Czaja, W.K., Young, D.J., Kawecki, M. &. Brown, R.M. Jr**. 2007 The Future Prospects of microbial cellulose in biomedical Applications. *Biomacromolecules*, vol. 8, no. 1, pp. 1-12.

**Dahlin, C., Linde, A., Gottlow, J. & Nyman, S.** 1988. Healing of bone defects by guided tissue regeneration. *Plastic and Reconstructive Surgery*, vol. 81, no. 5, pp. 672-676.

**Dweib, M.A., Hu, B., Shenton, H.W. III & R.P. Wool**, 2006. Bio-based composite roof structure: Manufacturing and processing issues. *Composite Structures*, vol. 74, no. 4, pp. 379-388.

**Elliott-Sink, S**. Special Report: Cars Made of Plants. 2005. *www.edmunds.com/advice/fueleconomy/articles/105341/article.html*.

**Evans, B.R., O'Neill, H.M., Malyvanh**, **V.P., Lee, I. & Woodward, J**. 2003. Palladium-bacterial cellulose membranes for fuel cells. ***Biosensors and Bioelectronics***, vol. 18, no. 7, p.917-923.

**Fontana, J.D., de Souza A. M., Fontana, C.K., Torriani, I.L., Moreschi, J.C., Gallotti, B.J., de Souza, S., Narcisco, G.P., Bichara, J.P. & Farah, L.F.** 1990. Acetobacter cellulose pellicle as a temporary skin substitute. *Applied Biochemistry and Biotechnology*, vol. 24-25, pp. 253-264.

**Govindarao, V. M. H.** 1980. Utilization of rice husk- a preliminary analysis. *Journal of Scientific & Industrial Research*, vol. 39, no. 9, pp. 495-515.

**Hart, J., Silcock, D., Gunnigle, S., Cullen, B., Light, N.D. & Watt, P. W.** 2002. The role of oxidised regenerated cellulose/collagen in wound repair: effects in vitro on fibroblast biology and in vivo in a model of compromised healing. *The International Journal of Biochemistry & Cell Biology*, vol. 34, no. 12, pp. 1557-1570.

**Helenius, G., Backdahl, H., Bodin, A., Nannmark, U., Gatenholm, P. & Risberg, B**. 2006. *In vivo* biocompatibility of bacterial cellulose. *Journal of Biomedical Materials Research Part A*, vol. 76, no. 2, pp. 431-438.

**Heller, J.** Use of polymers in controlled release of active agents in Controlled Drug Delivery. 1987. *In* J. R. Robinson & V. H. L. Lee, eds. *Fundamentals and Applications*, 2nd Edition, pp. 180–210, New York, Marcel Dekker.

**Huia, J., Yuanyuan, J., Jiao, W., Yuan, H., Yuan, Z. & Shiru, J**. 2009. Potentiality of Bacterial Cellulose as the Scaffold of Tissue Engineering of Cornea. In *Proceedings of 2nd International Conference on Biomedical Engineering and Informatics (BMEI 2009)*, pp.1-5.

**Iguchi, M., Yamanaka .S. & Budhiono, A**. 2000. Review Bacterial cellulose - a masterpiece of nature’s arts. *Journal of Materials Science*, vol. 35, no. 2, pp. 261– 270.

**Ikada, Y.** 2006. Challenges in tissue engineering. *Journal of the Royal Society Interface*, vol. 3, no.10, pp. 589-601.

**Jonas R.E. & Farah L.F.** 1998. Production and application of microbial cellulose. *Polymer Degradation and Stability*, vol. 59, no. 1-3, pp. 101-106.

**Kats, H.S. & Milewski, J.V.** 1987. *Handbook of Fillers for Plastics*. New York. Van Nostrand Reinhold.

**Kinoshita, T., Inoue, K., Iwao, K., Kagemoto, H. & Yamagata,Y.** 2009. A spatial evaluation of forest biomass usage using GIS. *Applied Energy*, vol. 86, no. 1, pp. 1–8.

**Klemm, D., Schumann, D., Udhardt, U. & Marsch, S.** 2001. Bacterial synthesized cellulose - artificial blood vessels for microsurgery. *Progress in Polymer Science*, vol. 26, no. 9, pp. 1561-1603.

**Kokta, V., Raj, R.G. & Daneauli, C.** 1989. Use of Wood Flour as Filler in Polypropylene; Studies on Mechanical Properties, *Polymer Plastic Technology and Engineering*, vol. 28, pp. 247.

**Kumari, T.V., Vasudev, U., Kumar, A. & Menon, B**. 2002. Cell surface interactions in the study of biocompatibility. *Trends in biomaterials and artificial organs*, vol. 15, no. 2, pp. 37-41.

**Kurpiel, F.T.** 1997. Diffusion of cellulose fibre-cement siding and roofing into North America. *In* A. A. Moslemi, ed. *Proceedings of Inorganic-Bonded Wood and Fibre Composite Materials*, pp. 41-44.

**Kurpiel, F.T**. 1998. Fibre-cement siding is tomorrow’s growth product. *Wood Technology*, vol. 125, no. 1, pp. 50-54.

**Leao, A. L**. 2005. Natural Fibres Based Composites - Technical and Social Issues. *Molecular Crystals and Liquid Crystals,* vol. 3, pp. 160.163.

**Leao, A.L., Cherian, B.M., Souza, S.F., Thomas, S., Pothan, L.A. & Kottaisamy, M**. 2011. Cellulose Nanocomposites for High Performance Application. *In* S. Kalia, B.S. Kaith ,I. Kaur. eds. *Cellulose Fibres: Bio and Nano-Polymer Composites - Green Chemistry and Technology.* New York: Springer Berlin / Heidelberg.

**Legnani, C., Barud, H.S., Quirino, W.G., Caiut, J.M.A., Ribeiro, S.J.L., Achete, C.A. & Cremona, M.** 2009. Transparent Nanocomposite Bacterial Cellulose Used as Flexible Substrate for OLED. *11th International Conference on Advanced Materials*, T559.

**Lönnberg, H., Fogelström, L., Samir, M.A.S.A.,** **Berglund, L., Malmström, E. & Hult, A.** 2008. Surface grafting of microfibrillated cellulose with poly(ɛ-caprolactone) – Synthesis and characterization. *European Polymer Journal*, vol. 44, no. 9, pp. 2991–2997.

**Longer, M.A. & Robinson, J.R.** 1990. Sustained-release drug delivery systems. *In* J. P. Remington, ed. *Remington’s Pharmaceutical Sciences, 18th edition*. Easton,Pennsylvania. Mack Publishing, pp. 1676–1693.

**Macedo, N.L., Matuda, F.S., Macedo, L.G.S., Monteiro, A.S.F., Valera, M.C. & Carvalho, Y.R**. 2004. Evaluation of two membranes in guided bone tissue regeneration: Histological study in rabbits. *Brazilian Journal of Oral Sciences*, vol. 3, no. 8, pp. 395-400.

**MacVicar, R., Matuana, L.M. & Balatinecz, J.J.** 1999. Aging mechanisms in cellulose fibre reinforced cement composites. *Cement and Concrete Composites*, vol. 21, pp. 189-196.

**Madihally, S.V. & Matthew, H.W.T**. 1999. Porous chitosan scaffolds for tissue engineering *Biomaterials*, vol. 20, no. 12, pp. 1133-1142.

**Mehta, P.K. & Monteiro,.P.J.M**. 1993. *Concrete: Microstructure, Properties, and Materials*. New York, McGraw-Hill.

**Mello, L.R., Feltrin, Y., Selbach, R., Macedo , G.Jr., Spautz, C. & Haas, L.J.** 2001. Use of lyophilized cellulose in peripheral nerve lesions with substance loss. Arquivos *de* Neuro-Psiquiatria, vol. 59, no. 2-B, pp. 372-379.

**Millon, L.E. & Wan, W.K**. 2006. The Polyvinyl Alcohol–Bacterial Cellulose System as a New Nanocomposite for Biomedical Applications. *Journal of Biomedical Materials Research Part B: Applied Biomaterials*, vol. 79B, no. 2, pp. 245–253.

**Mohanty, A.K., Misra, M. & Drzal, L.T**. 2005. Natural Fibres, Biopolymers, and Biocomposites. Boca Raton, Florida: CRC Press.

**Negrão, S.W., Bueno, R. R. L., Guérios, E.E., Ultramari, F.T., Faidiga, A.M., Andrade, P.M.P., Nercolini, D.C., Tarastchuck, J.C. & Farah, L.F**. 2006. A Eficácia do Stent Recoberto com Celulose Biossintética Comparado ao Stent Convencional em Angioplastia em Coelhos. *Revista Brasileira de Cardiologia Invasiva*, vol. 14, no. 1, pp. 10-19.

**Nehrer, S., Breinan, H.A., Ramappa, A., Shortkroff, S., Young, G., Minas, T., Sledge, C.B., Yannas, I.V. & Spector, M.** 1997. Canine chondrocytes seeded in type I and type II collagen implants investigated in vitro. *Journal of Biomedical Materials Research*, vol. 38, no. 4, pp. 95-104.

**Nemetz, A.P., Loures, D.R.R., Coelho, J.C.U., Repka, J C., Bueno, R.R.A., Dietz, U.A. & Mello, L.R.O**. 2001. Efeito estrutural da utilização de celulose biossintética e politetrafluoroetileno expandido como substitutos do peritônio em cães”, *ABCD. Arquivos Brasileiros De Cirugia Digestiva*, vol. 14, no. 2 , pp. 139-42.

**Novaes, A.B. Jr. & Novaes, A.B.** 1992. IMZ implants placed into extraction sockets in association with membrane therapy (Gengiflex) and porous hydroxyapatite: A case report. *The International Journal of Oral Maxillofacial Implants*, vol. 7, no. 4, pp. 536-540.

**Novaes, A.B. Jr. & Novaes, A.B.** 1997. Soft tissue management for primary closure in guided bone regeneration: surgical technique and case report. *The International Journal of Oral Maxillofacial Implants*, vol. 12, no. 1, pp. 84–87.

**Olson, D.G., Tripathia, S.A., Giannone, R.J., Lo, J., Caiazza,N.C., Hogsett,D.A., Hettich,R.L., Guss,A.M., Dubrovsky, G. & Lynd, L. R**. 2010. Deletion of the Cel48S cellulase from Clostridium thermocellum. ***Pnas*,** vol. 107, no. 41, pp. 17727-17732.

**Rowell, R.M**. 1995 A new generation of composite materials from agro-based fibres. *In* P. N. Prasas, M. E. James, T. F. Joo, eds. *Polymers and Other Advanced Materials: Emerging Technologies and Business Opportunity.* *Proceedings of the Third International Conference on Frontiers of Polymers and Advanced Materials*, Kuala Lumpur, Malaysia. pp. 66–69. New York, Plenum Press.

**Salata, L.A., Craig, G.T. & Brook, I.M**. 1995. *In-vivo* evaluation of a new membrane (Gengiflex®) for guided bone regeneration (GBR). *Journal of Dental Research*, vol. 74, no. 3, pp. 825.

**Sanadi, A.R., Caulfied, D.F., Jacobson, R.E. & Rowell, R. M**. 1994a. *Reinforcing polypropylene with natural fibres, Proceedings: International Jute and Allie Fibre Symposium on Biocomposites and Blends*. New Delhi, India, 163.

**Sanadi, A.R., Caulfied, D.F. & Rowell, R.M. 1994b.** Reinforcing polypropylene with natural fibres. *Plastic Engineering*, vol. 4, no. 27.

**Sanadi, A.R.,** **Young, R.A., Clemons, R.C**. **& Rowell, R.M**. 1994c. Recycled Newspaper Fibres as Reinforcing Fillers in Thermoplastics; Analyses of Tensile and Impact Properties in Polypropylene. *Journal of Reinforced Plastics and Composites*, vol. 13, pp. 54.

**Schumann D.A., Wippermann, J., Klemm ,D.O., Kramer, F., Koth, D., Kosmehl, H., Wahlers, T. & Salehi-Gelani, S.** 2009. Artificial vascular implants from bacterial cellulose: preliminary results of small arterial substitutes. *Cellulose*, vol. 16, no. 5, pp. 877-885.

**Seves, A., Testa, G., Bonfatti, A.M., Paglia, E.D., Selli, E. & Marcandalli, B**. 2001. Characterization of native cellulose/poly(ethylene glycol) films. *Macromolecular Materials and Engineering*, vol. 286, no. 9, pp. 524–528.

**Shah, J. & Brown , R.M.Jr.** 2005. Towards electronic paper displays made from microbial cellulose. *Applied Microbiology and Biotechnology*, vol. 66, no. 4, pp. 352-355.

**Shaikh, S., Birdi, A., Qutubuddin, S., Lakatosh, E. & Baskaran, H.** 2007. Controlled release in transdermal pressure sensitive adhesives using organosilicate nanocomposites. *Annals of Biomedical Engineering*, vol. 35, no. 12, pp. 2130–2137.

**Silva, E.C.** 2009. *Hidroxiapatita Sintética em alvéolo dentário após exodontia em Felis catus:Estudo clínico, radiológico e histomorfométrico*. Universidade Federal de Viçosa, Brazil. (MA thesis) .

**Svensson, A., Nicklasson, E., Harrah, T., Panilaitis, B., Kaplan, D.L., Brittberg**, **M. &** **Gatenholm**, **P**. 2005. Bacterial cellulose as a potential scaffold for tissue engineering of cartilage. *Biomaterials*, vol. 26, no. 4, pp. 419-431.

**Wan, Y.Z., Hong, L., Jia, S.R., Huang, Y., Zhu, Y., Wang, Y.J. & Jiang, H.J.** 2006. Synthesis and characterization of hydroxyapatite – bacterial cellulose nanocomposites. *Composites Science and Technology*, vol. 66, no. 11-12, pp. 1825-1832.

**Watanabe, Y., Mukai, B., Kawamura, K., Ishikawa, T., Namiki, M., Utoguchi, N. & Fujii, M**. 2002. Preparation and evaluation of press-coated aminophylline tablet using crystalline cellulose and polyethylene glycol in the outer shell for timed-release dosage forms. *Yakugaku Zasshi*, vol. 122, no. 2, pp. 157-162.

**Woodhams, R.T., Thomas, G. & D.K. Rodges**. 1984. Wood fibres as reinforcing fillers for polyolefins. *Polymer Engineering and Science*, vol. 24, pp. 1166.

**Yam, K.L., Geogoi, B.K., Lai, C.C. & Selke, S.E.** 1990. Composites from Compounding Wood Fibres with Recycled High Density Polyethylene. *Polymer Engineering and Science*, vol. 30, pp. 693.

**Yano, H., Sugiyama, J., Nakagaito, A.N., Nogi, M., Matsuura, T., Hikita, M. & Handa, K.** 2005. Optically Transparent Composites Reinforced With Networks Of Bacterial Nanofibers. *Advanced Materials*, vol. 17, no. 2, pp. 153–155.

**Yasuda, K., Gong, J.P., Katsuyama, Y., Nakayama, A., Tanabe, Y., Kondo, E., Ueno, M. & Osada, Y.** 2005. Biomechanical properties of high-toughness double network hydrogels. *Biomaterials*, vol. 26, no. 21, pp. 4468-4475.

1. *Projections to 2012: Hard Fibres, Jute, Kenaf and Allied Fibres*, FAO Consultation on Natural Fibres, Rome, 15‑16  December 2004. [↑](#footnote-ref-1)
2. *The Co-movement of Jute and Hard Fibres Prices with the Prices of Polypropylene and Crude Oil*, FAO Consultation on Natural Fibres, Rome, 31 January – 1 February 2007. [↑](#footnote-ref-2)
3. *Ibid.,* page 3. [↑](#footnote-ref-3)
4. *The Environmental Impact of Hard Fibres and Jute in Non-textile Industrial Applications,* FAO Consultation on Natural Fibres, Rome, 15 – 16 December 2004, based on analysis by Jan E. G. van Dam and Harriette Bos, Agrotechnology and Food Innovations (A & F) Wageningen UR, Wageningen, Netherlands. [↑](#footnote-ref-4)
5. For further information concerning the results of this and other recent CFC projects aimed at developing new markets for sisal, see the evaluation report for a cluster of CFC-funded projects on sisal development that was prepared for the CFC in 2010 by Paola Fortucci and Shakib Mbabaali and which covered the following: The umbrella project on Project and Market Development of Sisal and henequen Products (CFC/FIGHF/07); Cleaner Integral Utilization of Sisal Waste for Biogas and Biofertilizers (CFC/FIGHF/13); Sisal Fibre Replacing Asbestos in Cement Composites (CFC/FIGHF/15)and; Operationalisation of a Pilot Facility for a Continuous Sisal Fibre Extraction/Production Process (CFC/FIGHF/26FT). [↑](#footnote-ref-5)
6. The mission was composed of four experts: Paola Fortucci (team leader), Prof. Alcides Leao (technology advisor), Wilson Andrade (commercial advisor) and Ekaterina Krivonos (agricultural economist). The report of the mission includes a strategy for development of the sisal sector in Haiti and business models for the establishment of a pilot composite plant and of a centralized extraction facility. [↑](#footnote-ref-6)
7. Sisal Development: Sisal Fibre Replacing Asbestos in Cement Composites (CFC/FIGHF/15) – Project mid-term evaluation report, ADAS UK Ltd, 27 July 2009. [↑](#footnote-ref-7)
8. Ex-post evaluation of CFC/FIGHF/15, October 2010. [↑](#footnote-ref-8)
9. In Kenya, production data are currently being revised so as to reflect the expansion in production currently taking place in the smallholder sector. [↑](#footnote-ref-9)
10. Further details regarding the sisal biogas pilot project are contained in the evaluation report for CFC/FIGHF/13. [↑](#footnote-ref-10)
11. The environmental impacts are potentially very significant and beneficial. Further details are provided in the evaluation reports for CFC/FIGHF/13 and CFC/FIGHF/26FT. [↑](#footnote-ref-11)
12. ## Contributed by Prof. Alcides l. Leão, Bibin M. Cherian and Sivoney F. Souza, Sao Paulo State University (UNESP), Botucatu, SP, Brazil.

    [↑](#footnote-ref-12)