http://www.badana.eu/

The Badana project was conceived to develop an automated process to extract high-quality natural fibre from banana plant waste in order to exploit the fibres' properties as a sustainable reinforcement in polymer composites to be used in rotational- and injection-moulded products.
A consortium of 12 partners from across Europe have worked together over the last 2 years to address the specific technological problems of the small and medium-sized enterprises (SMEs) who have both driven and co-financed the project.
The full consortium is made up of 5 Research Service Providers (RTDs); 5 SMEs; and two end user companies. The entire supply chain is thus represented, providing a ready route to market for the project outcomes.

Organisational Information

Budget	€1M
Funding	€770k
Start Date	July 2009
Finish Date	June 2011
Duration (in months)	24
Lead Partner (Co-ordinator)	Smithers Rapra, UK

Participants

Agencia Estatal Consejo Superior de Investigaciones Científicas, Spain
BSH Electrodomésticos España, Spain
Colorex Master Batches, Netherlands
Grupo Antolín Ingeniería, Spain
Grupo Regional de Cooperativas Plataneras del Archipiélago Canario, Spain
PEVA, Hungary
Queen's University Belfast, UK
Rototek, UK
Sivel, Bulgaria
Smithers Rapra Technology, UK
Universidad de Las Palmas de Gran Canaria, Spain
Universidad de Zaragoza, Spain

The program of work was developed to benefit the SMEs involved in the production of bananas and SMEs that supply OEMs and end-users with sustainable moulded composite products in the automotive, packaging and consumer goods industries, by making significant technological advances in fibre extraction from waste material, and in the production of natural fibre, specifically banana fibre, plastic composites.

The research aimed to provide the SMEs with new market opportunities through satisfying the rapidly-growing demand of product manufacturers for ecoaesthetic (green) materials.

The key objectives of the project were:

- To develop high-quality banana fibre suitable to be applied to polymer processing such as injection moulding and rotational moulding
- To develop efficient and automated equipment for banana-fibre extraction.
- To develop new industrial applications for the waste from banana plants (false stem or leaves), thereby adding value for the benefit of SMEs in the agricultural sector.
- To increase the competitiveness of SMEs with new cost-effective, eco-efficient materials.
- To increase the technology level and competitiveness of the EU SME injection moulders, rotational moulders, compounders, farmers and end users through increased transnational collaboration, facilitating the production of value added products.

The project has successfully achieved these aims, turning a by-product of banana production into a valuable material for use in polymer composites, providing a sustainable and effective reinforcement material at a commercially and environmentally viable rate and cost.
The main objective of the Badana project was to develop and validate novel methods for the extraction and use of sustainable natural fibre from waste matter derived from banana cultivation in the EU.

There are approximately 25 thousand tonnes of this waste produced every year in the EU. Bananas grow on pseudo stems, which are superposed layers of vegetable matter, that only fruit once. The pseudo stems are removed from the plant when the bananas are harvested, and have traditionally been used as cattle fodder. The pseudo stems contain approximately 3% by weight of fibres, which when extracted can be used for handicrafts (weaving etc.), or other low value uses. The remaining pulp can still be used as animal fodder, although the rise of factory farming has made this a less attractive option in recent years, or as a compostable material.
Using the fibres as a natural reinforcement in polymer composites increases the value of the waste material, and does not displace food production, unlike some other commonly used natural fibres commonly harvested for this purpose, such as flax.
There are obvious benefits for the agricultural sector, through enhanced profitability, but also for compounders and moulders through the production of novel materials with a clearly demonstrable sustainability.

The first area to be addressed by the Badana project was the development of an automated extraction process for the fibres. Traditionally extraction has been done by hand, but this is a time consuming and labour intensive operation, which is not commercially viable on an industrial scale. The aim was to develop equipment that could be utilised by the farmers or cooperatives themselves, to enable highly efficient fibre extraction with consideration of ease of use, maintenance, economics, environmental impact and safety.

Once the fibres are able to be extracted in this way, there are a range of benefits to compounders, who are faced with an increasingly competitive market place, and a rise in demand for natural, sustainable fibre composites. It has long been recognised that using natural fibres for compounding with polymer materials is a key technology and will be increasingly important in maintaining and growing the prosperity of the EU plastics industry. Wider society recognises the need for environmental protection and sustainability, and the use of banana fibres offer a solution that does not displace food production, and aids preservation of natural resources.
In addition, preliminary studies on banana fibres showed superior mechanical properties compared to other natural fibres, adding to their appeal. The rise in demand for and production of natural fibre composite materials for a wide range of applications has paved the way for banana fibres to be utilised, and the Badana project built on the existing knowledge in this area and applied it to develop a range of composite materials with properties targeted to specific applications. The knowledge gained will allow the SME beneficiaries to capitalise on this, and to make further advances in the area, providing them with a market advantage and increasing their competitiveness.

Plastic parts manufacturers in the EU are under increasing pressure from low-wage economies and need new technologies and products to maintain their competitiveness in a keen market place. The green credentials of products are also becoming increasingly important to the consumer, adding to the potential benefits of using banana fibres in their products.
Research carried out within the Badana project has been focussed on a small number of target products, but the results are transferable and best practice guides have been developed to aid in the optimisation of both injection and rotational moulding applications. The fibres have been fully characterised providing an ideal opportunity for the EU SME community to capitalise on readily.
In addition, the project consortium has carefully considered the economic impact of the developments made, and has carried out a full life cycle analysis to demonstrate them.

The EU industry as a whole has a high knowledge base, and their advantage comes in producing technologically advanced and novel materials with a range of benefits such as light-weighting and sustainability, which are readily achievable with the incorporation of natural fibres into their products.

Through the routes outlined above, the Badana project aimed to help address the global competitiveness issues faced by the SME plastics sector in the EU.

The collaborative nature of the Badana project, allowing the SMEs to work closely with expert research organisations from across the EU, and to direct the research which they are co-funding, has meant that the results from the project are commercially relevant, and have led to the development of a range of industrially exploitable new technologies, materials and procedures.

The specific scientific and technological objectives of the project are as follows:

- To improve the efficiency of fibre extraction, decreasing the damage and loss of fibres during the process
- To design an innovative piece of equipment for fibre extraction, adapted to farmers' environments. The new equipment will enable secondary use of wastes (compost or animal feed) once the fibre has been extracted. This is possible because only 2 – 3% by weight of the fibre is useful for fibre-reinforcement purposes
- To reduce the cost of raw materials, relative to other natural fibres
- To extend fibre extraction processing to all seasons
- To provide optimal pre-treatment of banana fibres by tuxying, decorticating, drying, brushing, cutting and classifying
- To modify the fibres to maximise their applicability
- To optimise injection moulding and rotational moulding parameters
- To characterise the composites after processing (mechanical properties, degradability of fibre, etc.)
- To produce a design guide for banana-fibre-reinforced compounds
- To supply recyclable composites at lower cost
- To open up new markets for plastic products reinforced with banana

Each of the objectives has been designed to be measurable, and indicators were identified to determine whether each of them was successfully met within the project.

In addition to the clear technological advantages of the Badana project, there are also a number of clearly demonstrable societal benefits, such as:

- Improvements in the economic prosperity of SME banana cultivators
- Increased co-operation between material suppliers, converters, farmers, research centres and end users of the plastic products
- Increased competitiveness of European industry and in particular small- to medium-size businesses to maintain and grow this important sector
- Help to protect the jobs of the 1.5 million people working in the sector and to expand employment opportunities
- The development of new exploitation opportunities for the processes and formulations developed
- Improved skill levels throughout the supply chain

Banana trees from Canary Islands have been studied and analysed, in terms of their morphological and biological characteristics. Fibres obtained from their pseudo stems have been classified, according to the position of the leaves in the pseudo stem and to the variety of banana tree; this classification was made in order to determine if significant differences exist in mechanical properties, thermal behaviour, chemical composition or surface morphology due to these two factors. Fibres extracted from banana trees have been characterized by FTIR and TGA analysis, optical and SEM observations and mechanical tests. The characteristics obtained have been compared to those obtained for sisal fibres.

Starting from the manual procedures to extract banana fibres, a range of different ideas has been investigated to develop a prototype to produce banana fibres. Different stages have been followed, with several test and redesign phases, in order to achieve the initial prototype, named the MultiPhase Decorticating Machine (MPDM).

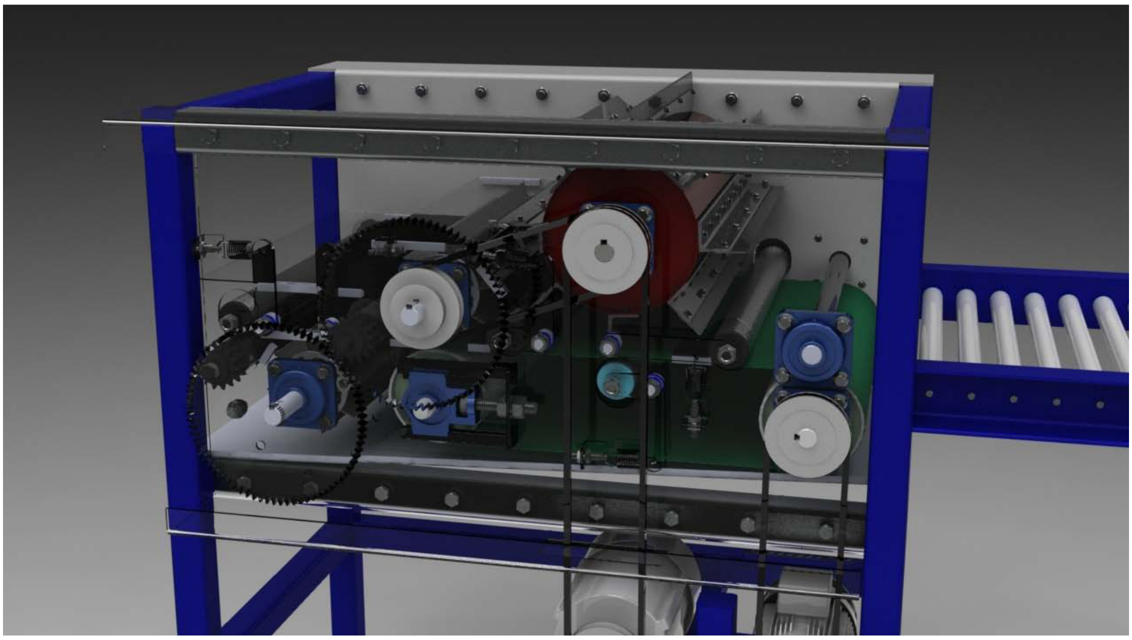

Figure 1: the MPDM – first prototype

This MPDM first prototype was extensively tested, and modifications undertaken in order to improve the amount of fibre extracted (and thus, the efficiency of the extraction process) and also the quality of fibre, as a prototype machine to obtain clean and high quality banana fibre was one of the main goals of the Badana project.
After considerable investigation into methods to improve the efficiency of the system and the quality of fibre produced it has been decided to separate the process in two different stages, obtaining first the tuxy and then a separate operation to scrape it to obtain the fibre.
Different modifications have been made to the prototype machine in order to improve the efficiency of the machine, both in terms of amount of fibre extracted and quality of the fibre obtained. The last equipment for fibre extraction has been redesigned taking into account the different trials carried out in the previous prototypes; this last prototype, called the RMDM (Reverse Movement Decorticating Machine), has been produced and tested, obtaining good results in fibre quality and production.

Figure 2: The RMDM – final prototype

The composite development was done in a number of subsequent stages, as outlined below.

Initially, fibre surface modification trials were performed using alkaline and acetylation treatments of banana fibres. The tensile properties of these fibres were then tested; the results show that tensile properties of treated fibres are lower than that of the pristine fibre.

Batch compounding trials of untreated and treated banana fibre reinforced polypropylene (PP) composites were carried out using a Gale minimixer and Hampden internal mixer. Maleic anhydride graft polypropylene (MA-g-PP) was employed as a coupling agent. Various formulations e.g. with different types and conditions of treatments and different MA-g-PP content have been examined. Alkaline and acetylation treatments have some effect on surface of fibres that leads to the change in interaction between fibre and polymer matrix. A detailed analysis of the mechanical properties and characterisation results enabled the compilation of a short list of formulations to be investigated further at pilot-plant scale.

Based on this short list, pilot-plant-scale twin-screw compounding trials of untreated and alkaline treated banana fibre reinforced polypropylene (PP) were carried out using the 21-mm Rondol twin-screw extruder. Maleic anhydride graft polypropylene (MA-g-PP) was employed as a coupling agent. This study compared the performance of the reinforcement effect of banana fibre on PP compounds with that of sisal fibre at 20 wt% content. Banana fibre presents better tensile and flexural properties of the compounds than sisal fibre. Mechanical properties are further improved in alkaline treated banana fibre filled compounds as a result of the better interaction with PP matrix. The relative performance is attributed to differences in the interaction between the fibres and the polymer matrix, the fibres' relative inherent stiffness and strength, and the aspect ratio of fibre after compounding and moulding operations.

The work was focussed through the drive of the SME partners towards a series of target applications such as an interior automotive part for GAS, kayaks for Rototek and the worktop of a washing machine for BSH. In each case, the special requirements of the product were considered. For example, the low odour requirements for interior automotive parts was achieved using alkaline treated banana fibre filled PP compounds. Industrial scale production of this compound has been carried out and subsequent injection moulding into product. Figure 3 shows the B-pillars, interior trim front pillars, made from alkaline treated banana fibre composite.
The end user evaluation of these trial parts has been very positive, and further work is ongoing beyond the timescale of the Badana project in this area.

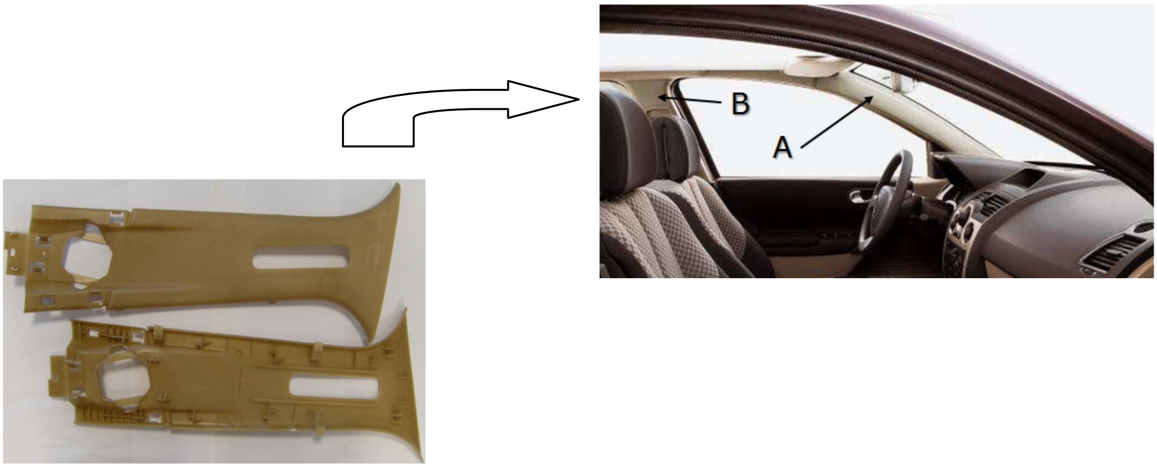

Figure 3: The B-Pillars (interior trim front pillars)

Large scale banana fibre filled PE compounds were produced for rotomoulding into kayaks. This material is used in the inner layer of multilayer product in order to increase mechanical properties, in particular stiffness. Figure 4 displays a kayak made by Rototek.

Figure 4: A kayak manufactured by Rototek

One of the BSH target applications is to replace the wood panel in the worktop of a washing machine with a banana fibre composite. The original product, as shown in figure 5, consists of a frame of white ABS and an insert made of wood. The wood panel is finished with a decorative sheet of melamine, either white or painted depending on the variant.
The replacement of this part by a fibre composite is expected to achieve enhanced decorativeness and functionality of this part.
Large-scale compound reinforced with 20% alkaline treated banana fibre has been prepared for industrial trials on this part.

Figure 5: Worktop of a washing machine produced by BSH

Rotomoulding developments were also made in a staged manner.
The advantages of moulding with natural fibre composite (NFC) materials have been clearly identified in terms of increased part stiffness through the use of a sustainable reinforcement source, however no such in-depth study has so far been attempted into the inclusion of natural fibre composite (NFC) reinforcement within a rotationally moulded product, hence no NFC rotomoulded products are currently available.
During the two years of the project, extensive industrial trials were carried out at QUB, culminating in the development of optimised procedures and a design guide for rotomoulding with NFCs, and more specifically with banana fibres.

Due to the large volumes of fibres necessary for rotomoulding, initial trials for proof of concept experiments were carried out using sisal fibres. This meant that once significant quantities of banana fibre were available, much of the ground work had already been covered, aiding the speed of development.

Initial work looked at compression moulding of plaques using both sisal and banana fibres in combination with a PE matrix. The plaques were subject to mechanical testing and analysis with DSC, FTIR and electron microscopy. The results showed that banana fibres composites are slightly weaker than those with sisal fibres; however, they can be considered a suitable reinforcement consideration with better fibre preparation.

The next stage of the work was to carry out a series of rotomoulding trials using a sisal fibre/ PE blend and a Caccia 1400R machine. The schematic in Figure 6 shows the constructions that were performed.

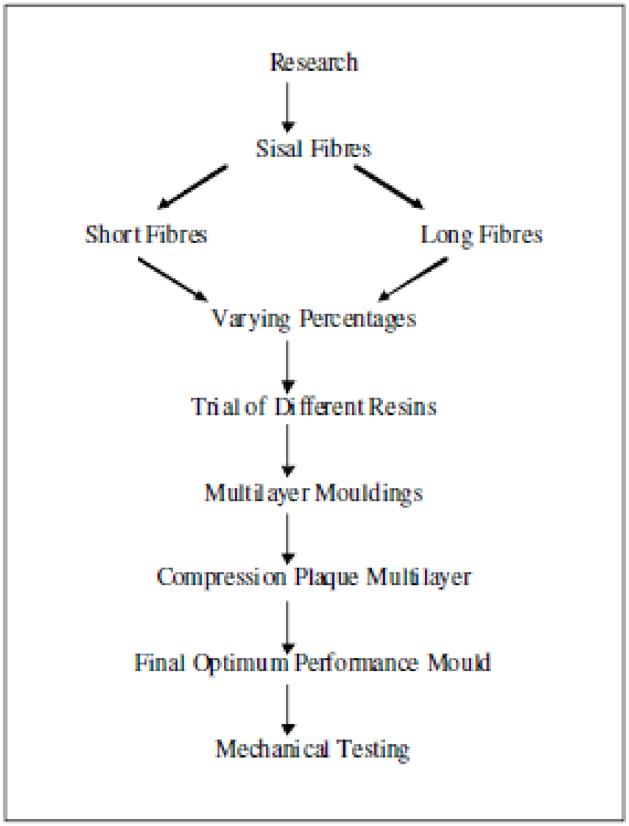

Figure 6: Schematic of initial rotomoulding trials

The main finding from this program of work was that not all the fibres were adequately bonded with the PE and the moulding; this resulted in being able to pull fibres out.
Further investigation determined that it was necessary to encapsulate the Badana fibre into the form of a pellet in order to maximise the coupling of the fibre / PE matrix with the rest of the moulding.

A further series of tests were then carried out using pelletised banana/ PE. The pellet was included at various thicknesses and at various parts of the moulding, either using a whole Badana pellet or a ground Badana pellet (grinding was carried out at QUB using a conventional PE grinding machine) This series of mouldings showed the best compromise between processability, part appearance and overall tensile strength and rigidity, and was used to determine the optimum processing parameters and to develop the design guide.

A final set of tests was carried out using foamed structures, in preparation for the industrial trials of kayak production, and again these results were used to develop the rotomoulding design guide.

Injection moulding developments were carried out in order to more fully understand the injection moulding process from the point of view of banana fibre composite materials.

In order to achieve this, several tasks were performed to obtain important results that from the point of view of the processing technique of injection moulding are essential to obtain plastic components of high quality and appearance.
Mechanical, physical and rheological properties are essential aspects that designers and processors should know in order to choose the right design and material for each type of plastic component and, in terms of processibility, to set up ideal processing parameters.

A test specimen injection mould was designed and mechanized (Figure 7), and test specimens were properly injected (Figure 8) and sent to CSIC (Centro Superior de Investigaciones Científicas) in Madrid, to perform mechanical characterization.

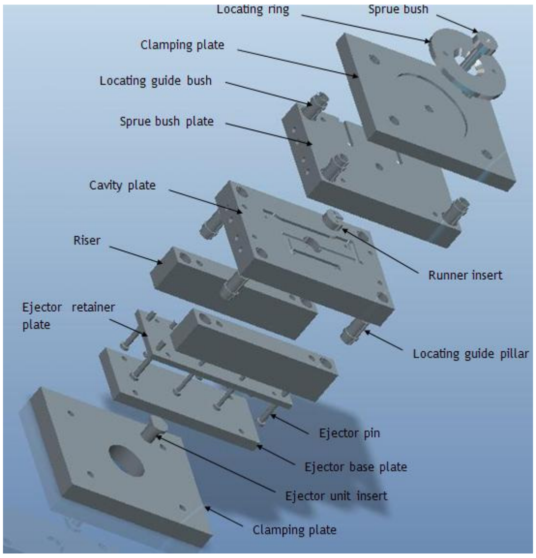

Figure 7: Test specimens mould, designed with ProEngineer


Figure 8: Tensile, flexural and impact standardized test specimens

Capillary rheometry was performed on the materials processed during the project and shear viscosity curves were obtained.
In addition, processing and degradation temperatures were established.

Injection moulding with a spiral mould (Figure 9) was carried out to evaluate the flow behaviour of the materials during processing, and comparative graphs were obtained.

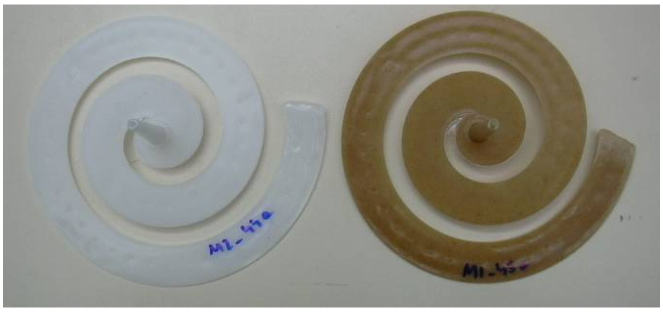

Figure 9: Spirals obtained during testing

Pressure transducers were located in the cavity of the spiral mould to measure the pressure drop when the injection temperature and speed were changed, and comparative graphs were obtained The influence of varying injection temperature and speed, over the rheological behaviour of the materials during injection moulding was studied.

In general terms, the tests performed showed that the compounding with banana fibres chemically treated, mixed with the right percentage of coupling agent and base material (PP BOREALIS BH345MO) has good mechanical and rheological properties that make it ideal to be processed by injection moulding, provided that processing parameters have been properly set up in order to avoid degradation of the banana fibres and therefore loss of mechanical properties.
These kinds of materials, due to the fact that natural fibres are coming from renewable sources and have low density compared with mineral fibres, are gaining high interest in industrial areas that demand recyclable materials with low weight and good mechanical properties.

Taking into account that injection moulding is one of the processes more widely used because of its flexibility, productivity and efficiency, among others, the material developed within the Badana project has huge opportunities to compete and fulfil the demands of companies that use these kind of materials already, or those that are on the way to find and implement new materials that are environmentally friendly.

During the two years of the Badana Project, much work has been devoted to the physio-chemical characterization of the different kinds of banana fibres from the Canary Islands from the point of view of the requirements to obtain composite materials based on thermoplastic matrices and short banana fibres according to the needs of the SME involved as beneficiaries of the Badana project. These results have helped significantly in the design and optimization steps of the final parts based on such materials.

Three different varieties of banana fibers (BF) were identified for the Badana's project development: Gran Enana, Gruesa Palmera and Pequeña Enana. Further exterior and interior were terms used to identify the leaf source of the fibre on each variety. Samples were identified by their respective Acronyms: GEE, GEI, GPE, GPI, PEE, PEI.

During the development and study of the composite materials, the characterization efforts have been concentrated on the cheapest and most versatile thermoplastic matrix polypropylene, the well known engineering member of the polyolefin's family. Thermal stability and mechanical behaviour issues have been the main driving powers of the work, looking for links between the obtained results and the morphology and microstructure of the composites emerging from the processing steps: mixing and moulding. The role of grafted maleated polypropylene as interfacial modifier from the matrix side on the composites has been ascertained as well as that played by the processing steps on the final performance of the composites.

In addition, several studies on polypropylene/sisal fibres (PP/SF) were conducted as a comparison to those based on banana fibres.

Initially, a background study was carried out to investigate the thermal stability of the banana fibres under different atmospheres by using the thermo gravimetric analysis (TGA) technique. The functional groups and structural changes in the banana fibres were identified by infrared spectroscopy aided by Fourier transform (FT-IR).
From the FT-IR characterization studies of the banana fibres, it was observed that no structural damage to the crystalline cellulose structures of the chemically treated banana fibres, nor changes in their crystalline cell were detected.
From the TGA results it was found that the alkali treatment affected the thermal stability of the treated samples. Nevertheless, the weight losses up to 388 ºC were almost the same for the pristine and treated banana fibres; the cellulose component was not removed or damaged by the alkaline treatments.
Tensile testing of post-processed single fibres was also carried out, on order to isolate their behaviour. From this work it was concluded that all the fibres reached the break point without to develop any effective cold-drawn mechanism to be recorded by the dynamometer. Values were in agreement with those found in the literature.

A morphological characterization of the banana fibres was also carried out, and a full correspondence between the results from the optical and scanning electronic (Field Emission) microscopies was achieved, as can be concluded from micrographs in Figure 10.

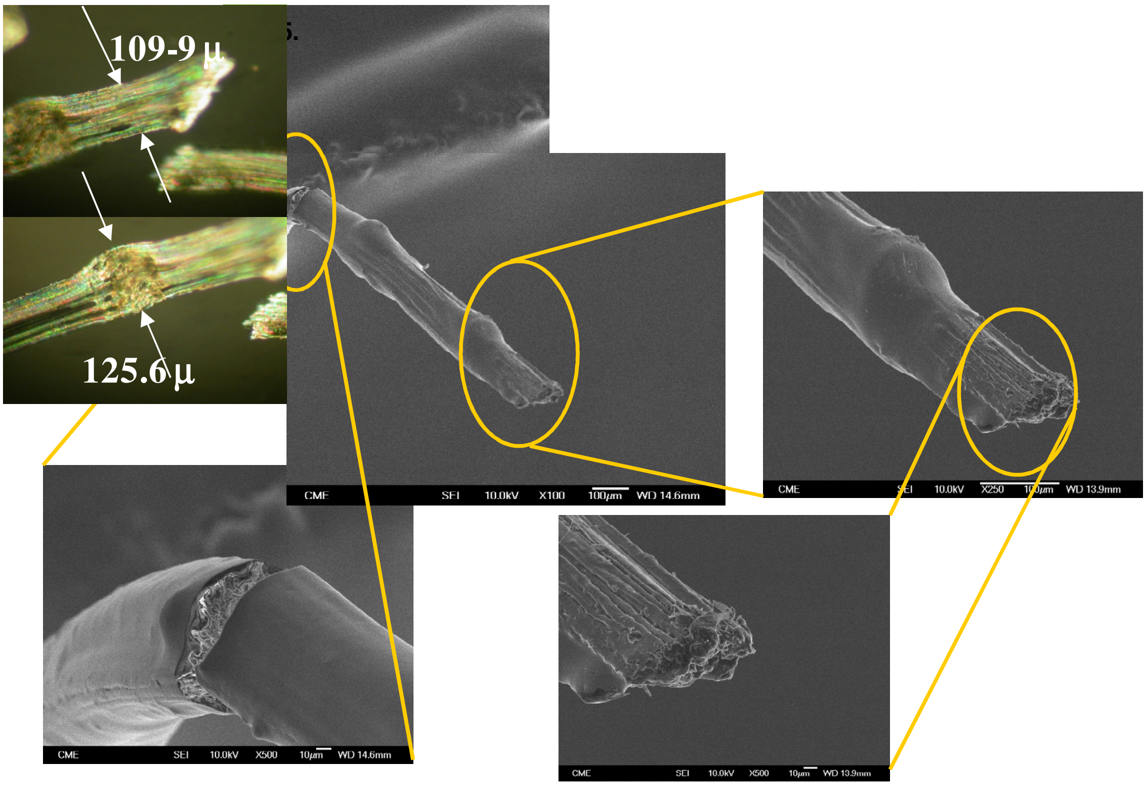

Figure 10: Correspondence between OM and FE SEM images

Sisal fibres showed a lower modulus value than the banana fibres, larger average strength values, but higher dispersion, and elongation at break values slightly higher than the banana fibres.

No significant differences were concluded between the different varieties of banana fibres characterized. All future work was then carried out on the PEI variety, which was chosen for availability reasons only.

The summary findings and conclusions of the characterisation work are as follows:

- Mechanical testing, fracture surfaces morphology, and thermal stability of the composites were the characterization routes chosen. Furthermore and because this study concerns discrete, short fibres, the changes in the particle size distribution and the mean particle size after the processing steps were ascertained by the selective extraction of the vegetal fibres from the injection moulded specimens.
- All the compression moulded composites based on PP and vegetal fibres showed tensile strength values between 30 and 40 percent lower than the neat polypropylene matrix. The tensile strength values increase in all the composites when a 5 % w/w fibre of maleated polypropylene as interfacial modifier from the matrix side was present on compounds. Variations ranged between 13 and the 26 percent lower than the neat PP, and even an increase of 8 percent was observed in the tensile strength values of the PP/alkali treated banana fibre composite.
- In addition, the tensile strength values increase in all the composites when a 10 % w/w fibre of maleated polypropylene was present on compounds as an interfacial modifier from the matrix

side. Nevertheless, the increases were lower than those obtained with just five percent of the grafted maleated PP.

• For the acetylated banana fibre composites, it was concluded that the presence of maleated polypropylene did not significantly affect the tensile strength values of the unmodified composite, which showed the highest value from all the PP/ vegetal fibre composites tested.

• FTIR analysis showed that the banana fibres underwent a strong chemical attack with the consumption of the easily available hydroxyls of cellulose. One may observe on the micrographs corresponding to the acetylated banana fibres sample, either in their side surfaces as in the cross section views, Figure 11, an extremely clean morphology if it is compared with the micrographs of the pristine banana fibre PEI.

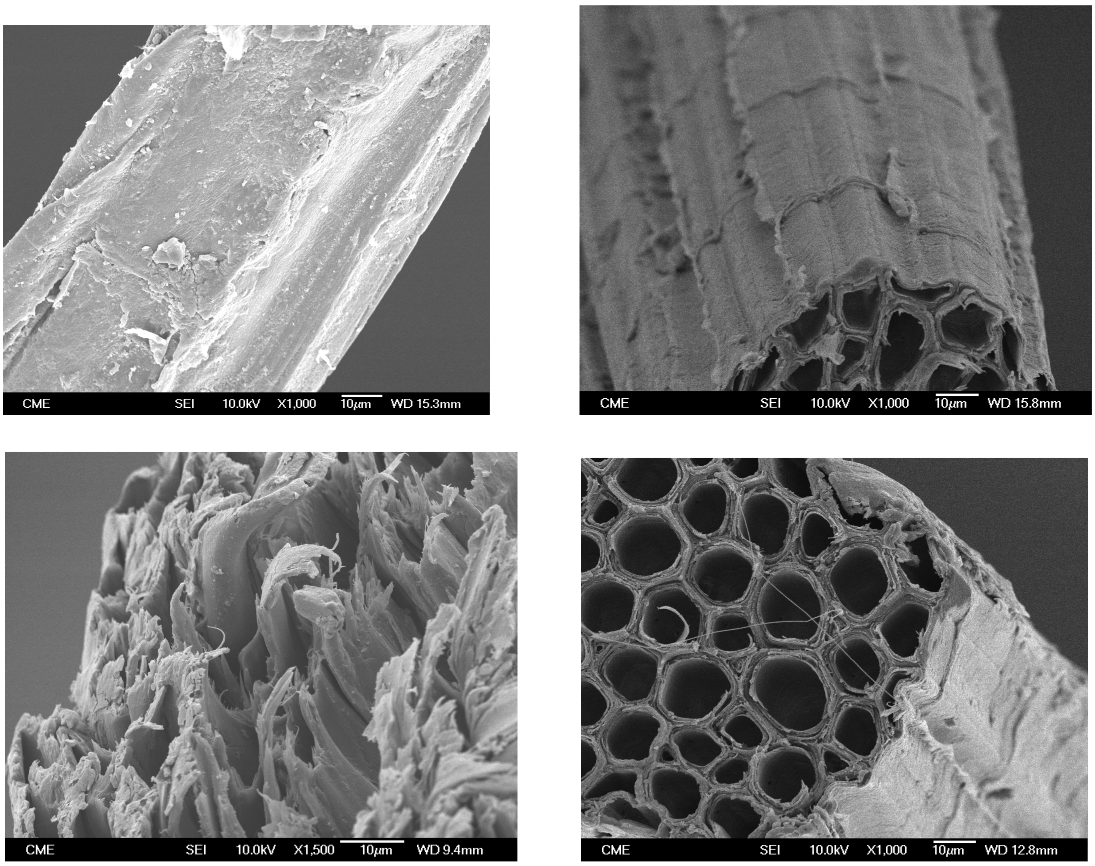

Figure 11: FE SEM images from the side surface (Top) and cross-sections (Down) of the pristine PEI Banana fibre (Left) and the acetylated treated banana fibre (Right)

• From the thermal stability studies for the compression moulded PP/treated banana fibre and PP/SF under inert atmosphere, it was concluded that the thermal stability of the composites based on the treated banana fibres shows a decrease of around 20 ºC if compared with that from the pristine banana fiber composites.

• The injection moulded composites were characterized in a similar experimental run to the compression moulded composites. Further injection moulded specimens were mechanized to obtain standardized specimens for flexural, impact testing and dynamic mechanical analysis (DMA).

• From the tensile strain/load curves obtained when testing the injection moulded composites, the differences in the fracture mechanism of the composites with respect to the injection moulded neat PP were evident. While the injection moulded neat PP was able to go on to the cold-drawn mechanism once it reached the yield point, all the composites break at this point. The presence of the banana fibres in the polypropylene matrix, when injection moulded, increases its elastic modulus by16.6 % while the sisal fibres have no effect on this parameter. In addition, when the banana fibres had been alkali treated, the elastic modulus increases by 44.4 % with respect to the neat PP.

- Better properties were observed in tensile modes for the PP/BF composites and higher impact strength for the PP/SF ones.
- The flexural elastic modulus values were very similar for all the PP/BF composites, showing and enhancement with respect to the neat PP. Nevertheless the sisal fibre composite showed a sharp fall in this parameter when the maleated PP was acting as the interfacial modifier from the matrix side.
- The flexural strength results for all the PP/BF composites showed an improvement for the modified composites in the presence of maleated PP as interfacial modifier, as compared to either the unmodified systems or the neat PP.
- As expected the flexural strain values were lower than that of the neat PP; the PP/SF showed the lowest. All the other composites yield at almost constant strain values between 30 and 40 percent lower than the neat PP matrix.
- From the selective fibre extraction results, it was concluded that the presence of the maleated PP, acting as interfacial modifier in the composites, increased the shortest size fraction of the pristine vegetal fibres, for both the sisal and the banana fiber composites, which agrees with the lower impact strength values at room temperature obtained for the maleated compounds when compared with the composites without interfacial modification from the matrix side.

The properties of the composites based on discrete particles are highly dependent on how well these are dispersed in the polymer matrix and also in the particle orientation degree as a function of the particles geometry and the shear and elongation flows, which may fracture them during processing operations. Breakage of fibres occurs on situations of poor stress balance between the fibres and the flows where they are embedded and are governed by the aspect ratio of the fibre, because there is a given threshold value below which the breakage cannot occur. The injection moulded composites based on banana fibres, with an aspect ratio twice as high as the sisal, have undergone eight times more fibre fracture processes than the sisal ones.

According the FE SEM study carried out it has been shown how the morphology and then the mechanical properties of the matrix changes according the processing conditions. From the panoramic images of the tensile fracture surfaces of the neat PP, compression or injection moulded it was observed how the compression moulded specimen broke before yield and even at large magnification the small holes (less than 1 micrometer) left by the nucleation agent from the additive pack of the PP grade, while the injection moulded specimen showed areas where the material was able to yield before break. It explains the six times larger break strain values for the injection-moulded material than for that the compression moulded one.

In addition to the confirmed variation in the size distribution of the vegetal fibres in the composites, the concentration of fibres, or much better the fibre/matrix ratio, needs to be optimized. Indeed, too low fibre concentrations increase the risk of heterogeneous, non uniform fibres distribution and inefficient packing, leading to matrix rich regions in the composite which favours an inefficient stress transfer all along the composite. The free volume fraction available in the polymer matrix to imbibe the reinforcement fibres is directly related to the interfacial modifiers role from the matrix side, as the maleated polypropylene, which must be able to enhance the interaction level between the matrix and the vegetal fibres, further to favour the optimal homogeneous distribution of the fibres.

The true possibilities to obtain composite materials based on banana fibre and PP with enhanced properties is clear from the project findings; there is a need for optimal compound and processing conditions for this material. It could be the start-up of correlations between composition and the processing operations conditions, mainly residence and cycle times, thermal, stress fields on each step and so on.

Further considerations about the variations in the fibre size during processing were concerned with the thermal stability of composites. Clean fibre surfaces, free from foreign substances, impurities or small particles, are required in order to get an acceptable and homogeneous wetability by the polymer matrix. Moreover, any foreign particle freely dispersed in the molten polymer may act as potential degradation site, either during processing or in the final part in use, giving rise to a non-useful material.

A life cycle analysis from cradle to gate was carried out to quantify and evaluate the environmental impacts of banana fibre extracted by the machine developed with in the Bandana project. SimaPro software Version 7.3 was employed in this study. The study was based on banana plantations in the Canary Islands, where 418,407 tonnes/year of banana are produced (55.18% of the European production). Banana fibres offer a truly sustainable material, as the raw material is the bio waste from banana fruit production, without the issues of water eutrophication and displacement of food crop production that accompanies crops that are grown solely for energy or materials production, such as flax, hemp and sisal. The developed process comprises of two steps, which are tuxy production and fibre extraction process.

The study of the environmental impacts of banana fibre extracted by the Badana process can be summarised as follows:

- No extra biomass wastes are produced in the banana fibre extraction process as the starting material is waste from banana fruits production.
- Life cycle assessment - Eco-indicator 99 Single score shows that fossil fuels and respiration inorganic compounds are the two main impact categories affected by banana fibre extraction process. The effect of the fossil fuels is directly link to the transportation of the tuxy from banana plantation to the extraction plant. The shorter the distance between the plantation that located the tuxy machine and the extraction process plant results in the lower the environmental impacts.
- The energy required in extracting banana fibre using the Badana process is approximately 11% of energy used to decorticate sisal fibre, hemp and flax fibres.
- The usage phase of natural fibre reinforced components offers significant ecological advantages in automotive applications where weight reduction is a primary consideration.
- Materials recycling and incineration are attractive disposal options for natural fibre product including banana fibre offering ecological benefits, which further enhance the assessment in their favour.

The economic and technical study of the Badana extraction process has been exercised based on 2 options, option A: Decorticating machine placed in the processing building and the tuxying machine located at each plantation and option B: Machine integrated on a truck.

Option A: Decorticating machine placed in the processing building and the tuxying machine located at each plantation

This study is based on the preliminary tests of the designed tuxing machine and the reverse movement decorticating machine (RMDM). The transport cost between the plantation and the processing plant is not included in this analysis because it is strongly dependant on the logistics involved. Another important thing to be taken into account is that the tuxying machine and the decorticating machine are independent machines, so each one needs an operator.

The production rate of the reverse decorticating machine was tested and measured, being about 18 kg/h. This production rate was extrapolated from 100 different tests (from different pseudo-stems) where each resultant fibre was weighed.

The RMDM shows very interesting behaviour in terms of quality of fibre and continuous work of the equipment, but the reverse movement strongly reduces the production rate related to whether no reverse movement is introduced. However the reliability and quality of process is a key point in favour of the reverse decorticating machine.

It is clear that labour cost has strong influence on the final fibre cost. Moreover, the need to have two different processes, tuxying in the plantation and decorticating in the factory, increases significantly the final cost.

The production cost of banana fibre is 0.43 Euros/kg. It seems to be high cost for extracting fibre, taking into account that there are some operations not included in this study (pre-processing of stems in the plantation).

In order to reduce the labour cost and increase the profitability of both processes, tuxying and decorticating should be developed simultaneously, as seen in the following proposal.

Option B: Machine integrated on a truck

As stated in the previous section that the solution of two phases in the process (tuxying and decorticating), placed on different locations is fine for the technical point of view but not so good from the economic point of view, mainly in the Canary Islands where the production is located in many small crops and several islands. An alternative to this could be to integrate both machines, in line, on a truck, which could make a route from plantation to plantation every day, with only one operator.

Advantages of this solution

- The cost of fibre is clearly less than the result of the other solutions before, mainly because the labour cost has been reduced.
- The logistics can be more easily optimised.
- The problem of managing big amount of wastes is considerably reduced.

- This solution enables to solve at lower cost the problem of releasing the fibres from the stems.
- The surface of plantations could be used for naturally drying the fibre (which requires significant surface, not easily available in a central factory)
- The function of the factory would be to collect only the fibres, to compact them, and to deliver them to customers.
- The work of farmers is reduced; only the work to store the stems and to keep the fibre is necessary.
- This is the best option for Canary Islands because of the small size and high numbers of plantations.

The resultant cost of fibre in Canary Islands (0.35 Euros/kg), considering a labour cost of 7 Euros/h, seems to be competitive, mainly if quality of fibre is according to requirements of customers.

Economic benefit to CoPlaCa

An economic analysis of producing banana fibre in the Canary Islands by CoPlaCa has been estimated. The study is based on the final technical solution implemented in the prototype equipment and the hypothesis as follows:

- The study is applied only to the farmers and cooperatives associated to CoPlaCa in all the Canary Islands with the total production of 700 tonnes/year
- The reference sale price of fibre is taken from the Abaca (the most similar fibre to banana fibre): 1.2 Euros/kg (in CoPlaCa processing building, transport outside the Canary Islands is not included))
- The study is based on RMDM and tuxying machine on a truck
- The cost in producing 1 kg of fibre is 0.35 Euros
- Total benefit for CoPlaCa (5 years) is estimated at 2,100,675 euros

There is expected to be a significant increase in the competitiveness of the SME proposers as a result of the Badana project. The SMEs have the knowledge and ability to produce innovative banana-fibre-reinforced composites compatible with injection- and rotational moulding requirements. Although Badana is not solely focused on the automotive industry as a target market, high demand is expected in this sector. However the advantage of natural fibre composites in general, and banana fibre composites in particular, is the wide field of applications beyond the automotive industry.
All members of the supply chain, from farmers to compound manufacturers to plastic transformers will directly benefit from this additional demand from end users.

In addition, the parallel development of new machinery and equipment for banana-fibre extraction has significant benefits in terms of either licensing or a new venture to capitalise on the developments. The economic evaluations carried out as part of the project form the basis for a business case.
In both cases, new machine development is a high-value post-project activity. Preliminary estimations show that at least one hundred and forty machines could be necessary, if all banana fibre in the EU were to be extracted.

The know-how and the intellectual property developed during the course of the project is owned by the SME participants and distributed accordingly:

CoPlaCa owns the know-how and the intellectual property relating to the fibre process and processing equipment. Colorex owns the IP for the compound formulations and procedures. Peva owns the IPR for consumer-moulded product design and optimisation using banana-fibre compounds. Rototek owns the technology for the rotationally-moulded products developed and for multilayer mouldings.

The main consumption of natural fibre composites is in the automotive industry, where almost 91% is used in compression-moulding applications. However, there is now a high demand by final users in several sectors for injection processing, owing to lower cycles time and better part quality. For this reason, the success of the Badana project opens the possibility that suppliers can better to respond to end users' demands.

Many new jobs will be created by the SMEs in the Badana project during the take-up of the technologies developed, mainly in farms for fibre extraction, specialist engineers in natural fibre composites and operators of extruders and injection-moulding machines. There will also be additional non-quantifiable cost savings due to:

- Profitable use of banana-plant wastes
- Banana fibre, as a by-product of food production, not displacing food production
- New companies working with banana composites will be created and other plastics manufacturers will work with these eco-efficient materials

It is also expected that the technology developed will also have applications in other natural fibre composite processing applications.
The best practice guides developed within the project will be an invaluable resource for the SMEs as they take the developments of the Badana project towards commercialisation.

The compounding industry and the polymer processing industries in the EU are dominated by SMEs that lack the resources to develop the innovative technologies they require to remain competitive. The developments of the Badana project give EU producers a technological advantage, and are therefore expected to have a significant economic impact throughout the EU for farmers, compounders and the plastic processing industry, as well as farm equipment manufacturers.

Although this project mainly attempts to improve the competitiveness of a group of SMEs, it has also provided some assistance to the fulfilment of EU policies, specifically:

- CO_2 reduction: The EU has committed itself to the Kyoto protocol (Directive 2002/358/EC), which aims to cut CO_2 emissions from the 1999 levels by 12% by 2010. One way to achieve this, without affecting gross domestic product, is by increasing the surface area of green plantations, which absorb CO_2 . CO_2 levels will be reduced if banana crops surfaces are used for a new activity such as fibre extraction, which is complementary to banana production. Economic problems for EU farmers could reduce the surface area available for crops, giving less surface area for CO_2

absorption. 2.5 million tonnes per annum of banana plants in EU crops reduce CO_2 levels by 3.75 million tonnes each year. In the case of banana cultivation across the world, the amount is considerable higher: 315 million tonnes per annum. This assumes an absorption of 1.5 kg of CO_2 for each kilogramme of plant grown. Production of oxygen in the EU as a result of banana crops is 2.5 million tonnes per annum. Therefore CO_2 levels would be reduced by 375,000 tonnes per annum if cultivation if bananas in the EU could be increased by 10%

- Recycling: At the end of life, plastic parts filled with glass fibre are difficult to recycle and the energy consumption is considerably higher than that needed to recycle natural fibre composite plastic parts, so this project will encourage recycling in line with the aims of the Landfill Directive (1999/31/EC)
- Reduced vehicle emissions due to lower weight: Due to their lower density, the new banana composites can reduce the weight of vehicles and consequent energy consumption, in accordance with the needs of the European vehicle exhaust emission directive (2002/80/EC)
- Framework 7 policy objectives: Badana has developed new eco-efficient materials and production processes and contributes towards sustainable development

The project has also contributed to the following EU social objectives:

- Quality of life: Through greater development of banana composites, new eco-efficient materials will be supplied to industry: this will open up new markets for natural fibres in general. Sustainable development is a high priority for European citizens – perhaps of even greater significance than product price – because they perceive that quality of live is strongly linked to long-term environmental quality
- Health and Safety and Working Conditions: The innovative equipment for fibre extraction developed within the Badana project will enable better working conditions for farmers and higher levels of safety since natural fibre composites are healthy materials for working and manipulating
- Employment and skill levels: New business activities will increase employment at the participant SMEs, mainly in farming, because intensive working time is needed. Skill levels in the fibre extraction process are less important; machine operators will be able to work with only a basic knowledge. The compounding process and processing of the composites developed within the project require a certain level of knowledge and skill by the engineers and operators. In this case, previous experience with other plastic materials is very important, but further training will still be necessary.
- Environment: Widespread adoption of the banana composites developed will lead to substantial environmental benefits in terms of CO_2 levels and increased recycling.

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