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Communication

Wood Polymer Composites Technology Supporting the Recovery and Protection of Tropical Forests: The Amazonian Phoenix Project

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Abstract: The Amazon Rain Forest has attracted worldwide attention due its large scale services to climate and also due to the green house gas emissions arising from deforestation. Contributing to the later and detrimental to the former, timber logging in the region has very low efficiency (only 16% in the production chain). Such timber extraction, often referred to as selective logging, has been claimed as a sustainable extractive industry, because the forest is said to restore itself through regenerative growth. But forest regeneration in the Amazon occurs naturally only in a very limited scale, resulting that large scale, low efficiency logging poses a big treat to the functional integrity of the biome, supplying to the market only a fraction of what it could if done differently. So, instead of extracting big centennial logs from the forests, the Amazonian Phoenix project proposes that large expanses of degraded lands be reforested using pioneer plants species from the forest itself. These plants have the capacity to heal gaps in the canopy, being able to grow and produce woody biomass in very extreme conditions. The idea is to mimic the regenerative dynamics of the natural ecosystem in short cycle agrosilvicultural production areas, utilizing a variety of technologies to transform raw fibers from these fast growth native plants into a variety of materials with high aggregated value. This communication presents the research on natural fibers by the Polymeric Composites Group within the Amazonian Phoenix Project. Sustainable technologies employing materials with good and responsible ecological footprints are important and necessary stimulus for a change in the destructive economical activities present in the Amazon frontiers. The relatively well established wood polymer composites technology, for example, is a good candidate solution. Two research and development fields are proposed: the first one considers production systems with simple and cheap machinery, to facilitate technology assimilation by rural communities in the Amazon. The second one aims at developing composite materials with advanced production technology, like profile and sheet extrusion and injection molding. The source of the fibers would be both the short cycle agrosilviculture with softwood species, on already deforested lands, and the hardwood residues from operating sawmills. Preliminary results show that softwood fibers act as potentially important reinforcement for synthetic plastics.

Keywords: polymer-wood composites; native plant fibers; Amazonian forest

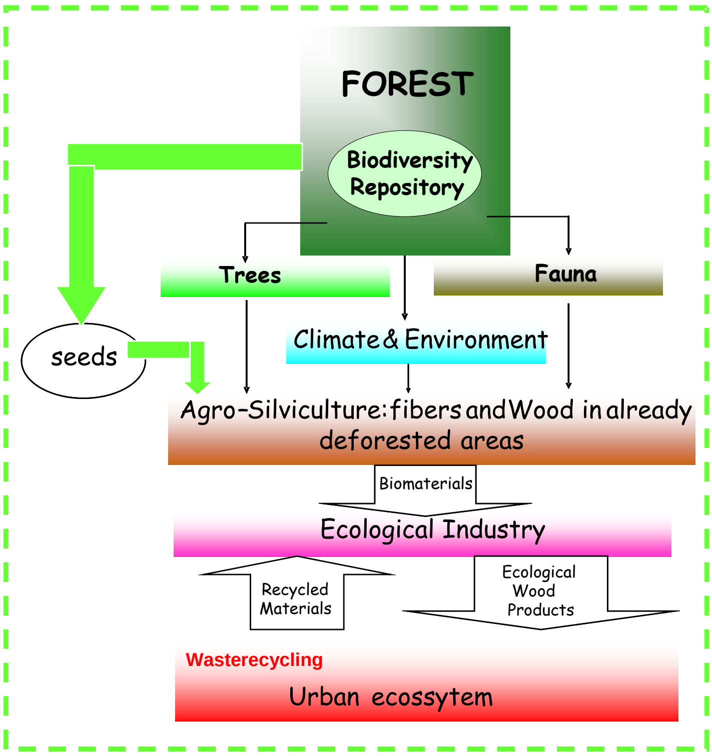
1. Introduction

Before the dawn of the industrial revolution, extractivism required that humans maintain harmonious collaboration with Nature and, in the case of abuse, led to its rapid collapse [1]. The advent of modern technology, however, gave rise to an uncontrolled increase in the demand for and use of natural reserves, with deleterious consequences to the planet. Climate change, global warming, imbalance of ecosystems and environmental disasters have awoken an increasing interest in the local, regional and global destructive effects of humans upon nature.

Brazil should play a fundamental role in the establishment of policies and strategies for maintenance of Earth's richest treasure trove of biodiversity, the Amazonian forest. With an area of dense forest covering approximately 5.5 million square kilometers, 3.6 million of which on Brazilian soil, this region contains an immense wealth and diversity of organisms, as well as the largest concentration of freshwater in the world, mineral deposits, timber, plant and animal species, on a list of resources of incalculable value. Currently the economic exploitation of such resources runs with little control, thus allowing for large scale devastation and deep impoverishment of the region. The deforestation in the Brazilian Amazon has for more than two decades sustained an alarming average rate of 18,500 square kilometers per year [2]. The National Institute for Space Research (INPE) estimates that, in just one year, the forest destruction was greater than the total area of the state of Sergipe in Brazil and only slightly smaller than the area of Belgium. In the last three years, annual deforestation rates have continued to exceed 23 thousand square kilometers [3]. Amazonia has a population of over 20 million people, 62% living in urban areas, mainly Belém and Manaus, the two largest cities in the region, and the other 38% scattered throughout wide expanses of forest [4].

A more inspired and sustainable driver for the Amazonian development will pose economically palatable and ecologically viable solutions, which can lure the agents of destruction into converting to more constructive activities. Over a period of seven years, one of us (A.D. Nobre) outlined a series of ideas and observations from experiences shared with several colleagues, synthesizing a wide array of fundamental and applied research collected over 20 years in the Amazon. That work resulted in the *Amazonian Phoenix Project—a Proposal for the Construction of an Ecosystem of Sustainable Enterprises in Amazonia* [5]. For a brief illustration, the diagram in Figure 1 shows the principal components of one of the production systems that inspired the early development of the Amazonian Phoenix ecosystem. The forest is connected to the deforested areas first through its environmental services, that is, helping dissipate heat, regulating the amount and quality of rain-forming aerosols, increasing moisture in the air, promoting rainfall, attenuating storms, removing damaging pollutants from the air, supplying pollinators and predators for pests, *etc*. The seeds of forest species will then be the main ingredients of production systems that will allow for the restoration of the degraded ecosystem, thus in turn recreating considerable portion of its lost environmental services. Associated with restored forest ecosystems, sustainable areas will be set aside where new forms of production for timber, fibers, biofuels, food, *etc.* will be developed. All the ecological materials and services thus generated cannot become economically sustainable without aggregating value to them, so the proposal calls for industrialization of rural areas of Amazonia, which will produce wealth through technology and design, for example, of high grade ecological wood products. Lastly, the connection with the urban ecosystems is made through the collection of recyclables in the garbage stream and convert them into raw materials to be used in the manufacture of ecological wood products such as furniture, houses, and a vast array of artifacts.

Figure 1. Principal components of one of the production systems of the Amazonian Phoenix ecosystem.



It is not the purpose of this article to present a complete description of the lengthy Amazonian Phoenix Project [5], which calls for a multidisciplinary effort of professionals from an array of diverse areas. Any reader interested in learning about the project may contact its author by email. The objective of this article is to reproduce in summary the encompassing context of the Amazonian Phoenix Project and to introduce just one of its iconic areas, the production chain of polymer composites with native plant fibers. We thus hope to awaken the interest of the scientific and technological community in collaborating with the development of new technologies in this area that can be used for the recovery of degraded areas in Amazonia and elsewhere in the world.

1.1. The Production Chain of Composite Materials in the Amazonian Phoenix Project

The production chain of composite materials in the Phoenix project is based on raw fibers produced in short-cycle silviculture with Amazonian species, imitating the forest's natural process of recovery in response to disturbances. The ecological fibers are then utilized in the fabrication of wood-thermoplastic composites using technology that is today one of the most important topics of Research and Development in the area of polymeric materials. On a limited scale, disturbance of the tropical forest also occurs through storms and other natural processes. As a consequence ingenious mechanisms to recompose or heal the canopy take place through the natural process of gap regeneration in clearings. There are pioneer species that take advantage of the sudden availability of light and space, such as "embaúba" *(Cecropia sp*), "marupá" (*Jacaranda copaia*), "caroba" (*Jacaranda micrantha)*, "lacre", among many others, which are also called gap-colonizing species. These species form a dense secondary forest, thus creating conditions for the complex, massive and long-standing tropical forest to recover through long-term ecological succession. Inspired on these natural systems, it has been demonstrated that many of such pioneer plant species can be cultivated with the purpose of harvesting plant fibers and wood. These plants grow at extremely fast rates, e.g., balsa wood (*Ochroma pyramidalis),* which grew 14 meters in 14 months in a plantation on degraded pastureland near Manaus [6]. These white softwood trees can be harvested in cycles of one or two years, generating short-term income for settlers and other farmers. Other arboreal hardwood species that require shade and protection to develop can be cultivated under the shade of these fast-growing pioneer trees, such as mahogany (*Switenia macrophylla*), "cumarú" (*Dipteryx odorata*), and "angelim" (*Hymenolobium*), among others (Figure 2). In 5 to 8-year cycles, these hardwoods with small diameters (10 to 20 cm) can be harvested to produce laminated and other engineered woods for use in civil construction. Additionally, 25-year cycles can be chosen for conventional sawable timber (with diameters larger than 30 cm). The annual or biennial production of softwood proceeds until the crowns of the slow-growth trees (hardwood) touch, forming a dense canopy. After the hardwoods are harvested, the cycle with the softwoods can begin again, thus renewing the production plan indefinitely and thereby reconstituting the ecological corridors for fauna and also working as an ecological base for pollinators. The intensive cultivation of these fast-growth and slow-growth forest species for fiber and wood production presents a considerable number of technical challenges that will require the use of all the available knowledge.

Figure 2. Illustration of the Phoenix Project concept.

This ecological silviculture proposal seems rather simple, but it is likely that problems may arise, so there is a need for the involvement of professionals from various areas of expertise. For example, a problem that is foreseen is predation of young tree saplings by wild animals such as rodents and deer, and domestic animals such as cattle and goats. One of the solutions adopted by local farmers in Amazonia to isolate their plantations from this type of attack can be applied to the silviculture proposed by the Phoenix project: a hedge of species with thorny trunks planted around the perimeter of the plantation, such as the "pupunha" (*Bactris gasipaes*) palm. The proximity of thorny trunks does not invite the passage of predators, thus keeping the internal area intact. In addition, the hedge itself will supply a series of foods and materials with a potential for use on the rural property itself or for sale (straw for basketwork, plant fibers for composites, fruit, palm heart, wood for furniture, food for animals, *etc.*). It should be noted that the species cited here merely exemplify production systems, but an infinite number of other species could also be used. A large variety of short-cycle plants can be cultivated, such as food plants, green fertilizers, medicinal plants, and even oil plants, among numerous other options. These integrated production systems (fiber, wood, food, animal feed, essences, and biomass energy, among others) will evolve, cycling through phases of succession that could provide their dynamics based on the natural system and respond with great flexibility to internal problems, such as pest attacks, and even external conditioning factors such as consumer market fluctuations.

Considerable interdisciplinary efforts will be required in the investigation of the reason for the success of the forests planted by local farmers, which resemble the chaos of a "capoeira" fight, in sharp contrast to the resounding failure of innumerable monoculture tree plantations in the forest. Perhaps the secret lies in studying the ecology, biology, diseases, and biogeochemistry not of managed forests but of the luxuriant and productive native forest itself, for therein lie all the solutions, tested and approved by millions of years of precious biological evolution. Gaining an in-depth understanding of how Nature does things will make it much easier to apply these solutions to managed systems. Obviously, these studies will not be conducted by researchers in the area of composite polymers with natural plant fibers, but it is up to these professionals to evaluate the immense range of fibers and woods available in the biodiversity of plants and to indicate the ones that would add the most value to the products supplied by short-cycle silviculture. The intelligent agro-silviculture model of the Amazonian Phoenix project, with its rich portfolio of solutions for land use, rehabilitation of degraded areas, protection of forest fragments, and recovery of the Amazonian biome in its environmental services could be inseparable from what we describe as the triggering of multiple production chains and value addition. The goal is to enable industrialization to reach the rural boundaries. Two lines of research and development could advance in the area of polymer composites containing natural plant fibers: one line that would work with production systems using relatively cheap and simple machinery, enabling rural communities in Amazonia to absorb this technology; while the other line would develop composite materials using more advanced manufacturing technology, such as the extrusion of profiles for civil construction, the injection of plastic parts, *etc.*, whose developed technologies could be absorbed by industrial areas such as the Manaus industrial zone. Thanks to its biodiversity, Brazil could be a pioneer in many technologies. The destruction of the forest not only would endanger South America's hydrological cycle, but we would also lose the chance of sustainably exploiting an uncountable number of plant and animal species, with the natural technologies they involve.

It should be emphasized that although a large part of the technology involving the use of wood flour in thermoplastic composites was developed for species of eucalyptus and pine, it would make no sense to use these species in the Amazonian region, since they are very poor in intrinsic qualities and environmental services when compared with the tropical forest. However, save for particularities of the plant fibers and species of Amazonia, the same principles could be used in the production of thermoplastics containing natural plant fibers, adding value to these fibers.

1.2. Polymer Composites Containing Natural Plant Fibers

In recent years, there has been increasing worldwide interest in the development of new technologies involving the use of products that cause lower environmental impact. In this context, special attention has focused on synthetic plastic materials since they lead to several questions that require attention, particularly non-biodegradability and the difficulty of recycling, which ends up by generating vast accumulations of this type of material in deposits, garbage dumps, and in the environment itself [7].

In the search for a solution to this problem, various researches and works in the area of polymeric composites have and are still being conducted to ensure environmental conservation and to provide a better living standard to society as a whole. Among the researches in this area that have been growing and stand out are those that seek applications for natural modifiers, mainly in terms of the use of natural fibers [7-9]. Natural fibers are fibers found in nature and used raw or after treatment. Natural fibers are divided into fibers of animal, vegetable, and mineral origin.

Emphasis should be given to the use of natural fibers of plant origin, due to the enormous biodiversity of available plants that can be investigated and because they represent a renewable resource. Several natural plant fibers are produced in practically every country and are usually called lignocellulosic materials [8]. Brazil has a wide variety of plant fibers with different chemical, physical and mechanical properties. The natural plant fibers and fillers, originating or not from wastes, that are cited in the specialized literature as potential modifiers of thermoplastic polymer [7,10] are: Native Brazilian fibers: sisal, coconut, jute, ramie, "curauá", sugarcane and soybean bagasse; Fibers from other countries: kenaf, fique and hemp; Starches; Wood wastes: these wastes are commercially called wood flour or sawdust; Husks of rice, wheat and other cereals. Table 1 lists some of the mechanical properties of natural fibers and fibers used conventionally as reinforcements in composite materials.

Table 1. Values of density and mechanical properties of natural fibers and fibers sued conventionally as reinforcements in composite materials [11,12].

Fiber	Density (g/cm^3)	Elongation (%)	Tensile strength (MPa)	Young´s modulus (GPa)
Cotton	1.5–1.6	7.0–8.0	287–597	5.5–12.6
Jute	1.3	1.5–1.8	393–773	26.5
Ramie	-	3.6–3.8	400–938	61.4–128
Flax	1.5	2.7–3.2	345–1,035	27.6
Sisal	1.45	3.0–7.0	468–640	9.4–22
Coir	1.2	30.0	175	4.0–6.0
Glass-E	2.5	2.5	2,000–3,500	70.0
Glass-S	2.5	2.8	4,570	86.0
Aramide (normal)	1.4	3.3–3.7	3,000–3,150	63.0–67.0
Carbon (standard)	1.4	1.4–1.8	4,000	230.0–240.0
Curauá	1.0–1.3	4.2	700–1,100	26.0–46.0

Several products are being developed using natural plant fibers, mainly for internal finishing parts for vehicles, where other mechanical, thermal and acoustic properties are relevant. Some fibers occur spontaneously in nature and/or are cultivated as a farming activity. Natural fibers can also be called cellulosic fibers, since cellulose is their main chemical component, or they can be called lignocellulosic fibers when one takes into account that most fibers contain lignin, a natural polyphenolic polymer [13]. The range of uses of natural fibers is very large, encompassing classical applications in the textile industry, as reinforcements in thermoplastic and thermoset polymer matrices and, more recently, as absorbent materials for heavy metals used in the treatment of industrial wastes, among other applications.

The processing of thermoplastic composites modified with natural fibers is very complex due to the hygroscopic and hydrophilic nature of lignocellulosic fibers. The tendency of lignocellulosic fibers to absorb humidity generates the formation of vapor during processing [13]. For injection molded products, the formation of gases is problematic because volatile substances are trapped within the cavity during the injection molding cycle. If the material is not dried properly prior to processing, it will lead to the formation of a porous product with a structurally expanded microstructure. The pore distribution is influenced by processing conditions, and will therefore impair the mechanical properties of the modified material. The presence of absorbed water can also worsen the thermal degradation of cellulosic material. Its hydrolytic degradation, which is heightened when the temperature of the melted polymer reaches 200 °C, is accompanied by the release of volatiles. Another disadvantage of the use of lignocellulosic fibers is that, besides hydrolytic degradation, they have another processing temperature limitation, since they present a mass loss onset temperature (~220 °C) due to the hemicellulose.

Several additional techniques have been proposed to improve the properties of plastic modified with lignocellulosic fibers. The addition of processing aids such as calcium stearate and polyethylene waxes, and of compatibilizers such as functionalized polymers, improves the processability and/or introduces greater polarity in the polymeric composite, enhancing the dispersibility of lignocellulosic fibers [14]. The surfaces of lignocellulosic materials contain polar hydroxyl groups which are due mainly to cellulose and lignin, and these polar groups interact very easily with polar polymeric matrices.

In general, the main advantages of natural fibers [8-10,13,15] are:

- Plant fibers are renewable materials and their availability can be considered unlimited.
- Due to the enormous diversity of woody and fibrous plants available in nature (65 thousand species of vascular plants in Amazonia, more than six thousand of which are trees), there is a huge potential for the discovery of natural fibers with desirable properties (mechanical strength, chemical and biological stability, fire resistance, lightness, abrasion resistance and shear strength, among other properties of interest.
- Natural fibers are less abrasive than the artificial fibers normally used as reinforcement, e.g., glass fibers, and thus cause less wear of the equipment employed in their processing.
- They are biodegradable materials, a crucial characteristic for components that must be discarded at the end of their service life.
- Composites reinforced with natural fibers, which also use biodegradable matrices, are considered the materials that are the least harmful to the environment and can be composted at the end of their use.
- Natural fibers represent a new source of income for rural populations, and can thus help stem the enormous influx of rural populations to urban centers, a phenomenon that has occurred principally in the country’s northern and northeastern regions.

- Natural fibers have low density and high deformability when compared with similar materials in this field of application.
- Lastly, their cost is low compared to that of the reinforcements currently utilized.

Polymer composites with natural fibers have also been indicated as potential and economically viable alternative for the fixation of carbon in nature, also reducing CO_2 emissions into the atmosphere during their cycle of production, processing and use, thus adding to their economic potential due to the possibility of trading carbon credits for the production chain. In August 2006, a ton of carbon was quoted at $15 to $18 Euros (a year earlier the cost was $5 Euros), a value that is expected to rise to $30 or $40 Euros between 2008 and 2012, when the reduction of 5.2% of combined carbon emissions in the atmosphere ($CO_{2equivalent}$ in relation to the 1990 emissions) comes into force, as established by the Kyoto Protocol. It is estimated that polymer composites with plant fibers store on average 325 kg carbon per metric ton during their service life [16].

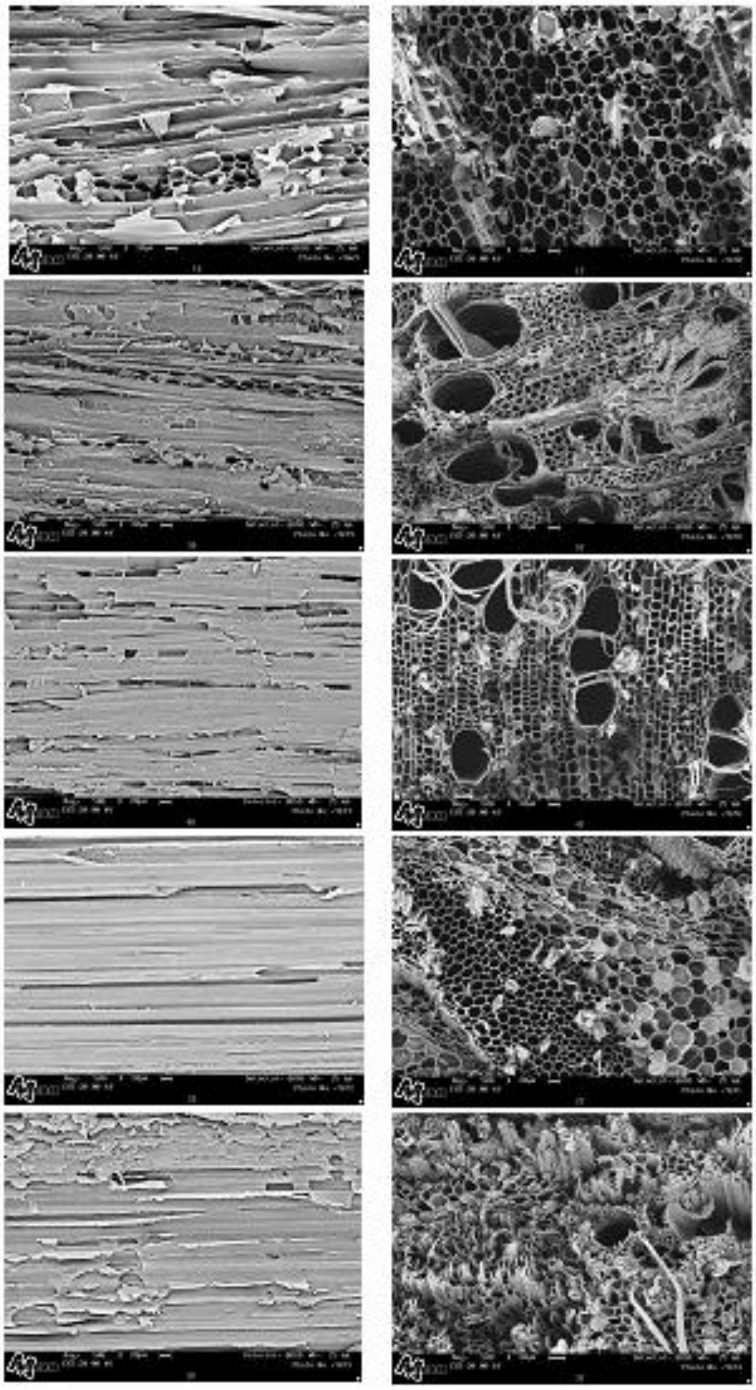
1.3. Study Plan of the Composites Group of the Amazonian Phoenix Project

The initial studies of the Phoenix composites group are being carried out with the purpose of testing the viability of using wood fibers of balsa and embaúba, and fibers of bamboo and the castor bean plant in composites with thermoplastics, particularly polyolefins and PVC recycled from urban waste. The thermogravimetric analysis (TGA) of the fibers will indicate the ultimate temperature for use of these fibers and, hence, the most suitable thermoplastic matrices for the preparation of composites. Thermoset matrices may also be used, with the advantage that their processing temperatures are much lower than the processing temperatures of thermoplastic matrices. Knowledge of the internal structure (anatomy) of fibers in important, indeed crucial, since, besides helping the identification of species, understanding physiological processes, and clarifying mechanisms of adaptation of vegetables to different environments, it supplies information such as roughness, pore size (veins) and fiber lengths. All of these factors are directly related to the capacity of adhesion at the fiber/polymer matrix interface (compatibility) and the capacity of homogenization and, hence, the final mechanical properties of the composite. Initial studies of the internal structures of fibers have been performed by scanning electron microscopy (SEM). Figure 3 shows SEM micrographs of the longitudinal and transverse surfaces of fibers of balsa wood, embaúba, castor bean, and two species of bamboo in the raw (natural) state, *i.e.*, their original state. The SEM images were obtained using a scanning electron microscope from Zeiss model Stereoscan 440 at 20 kV. These micrographs reveal long continuous fibers and veins of different shapes and sizes. The composites group is currently engaged in studies on the treatment of fiber surfaces, as well as on the length and size of pores of fibers.

Studies of the internal structures of plant fibers revealed the presence of natural and artificial impurities on the surface of these fibers resulting from treatment [17-19]. These residues on the surface of fibers reduce their adhesion when they are used in composite or laminated materials. Another study [20] found that washing sisal fibers in water partially removes impurities on their surface, leaving it rougher, which may increase adhesion at the fiber/matrix interface. Another treatment to improve the adhesive characteristics of the surface by removing impurities is called mercerization (10% NaOH solution), which has been used extensively to treat cellulosic fibers. Mercerization increases the surface tension and therefore the wettability of fibers, and also improves bonding through a mechanical form of interlacing between the matrix and the rough surface of fibers. Mercerization also causes defibrillation of fibers, *i.e.*, the disaggregation of fibers into microfibers, thus increasing the effective surface area available for contact with the liquid matrix. Reports in the literature [21] state that many composites in which mercerized fibers were used showed higher mechanical properties than composites containing non-treated fibers. The treatment of fibers with ionized air is another method for improving fiber/polymer matrix interfacial adhesion. The viability of this treatment was evidenced in curauá fibers treated with ionized air in the molding of phenolic composites [22].

Figure 3. SEM micrographs of the longitudinal and transverse surfaces of fibers of (a) balsa wood, (b) embaúba, (c) castor bean, and (d, e) two species of bamboo in the raw (natural) state, *i.e.*, their original state.

(a)
(b)
(c)
(d)
(e)



Data in the literature on the performance of fiber-reinforced composite materials indicate that the critical length (or the critical aspect ratio) of fibers depends on their volume fraction in composites. In general, the higher the aspect ratio the lower the critical volume fraction [23,24]. The strength of composites containing a low volume fraction of fibers is little influenced by the fiber. In this case, the fibers act as defects, embrittling the matrix and thus reducing the composite's mechanical strength. Above a critical fraction, the strength of composites increases as the fiber content in the matrix increases.

Coupling/compatibilizing agents should also be used to improve the fiber/matrix interface and aid the flow to increase processability. Fillers such as talc can also be used to further increase the stiffness of these composites. Expanding agents may also be tested with a view to reducing the density of composites. Therefore, the effects of treatment on fibre/matrix interface and the critical lengths of fibers will be investigated in next studies. In parallel to the proposed studies, an investigation into the recyclability of the composites will be conducted in future studies, focusing on the life cycle of these products.

In the medium term, based on the prospection of plant biodiversity, the aim is to create a Library of Natural Plant Fibers of Amazonia, in which fibers will be characterized and their potential use in thermoplastic and thermoset composites will be evaluated.

2. Conclusions

Recalling Dr. Covey's revolutionary thinking as a reminder of key principles: "Couldn't synergy create a new script for the next generation—one that is more geared to service and contribution, and is less protective, less adversarial, less selfish; one that is more open, more trusting, more giving, and is less defensive, protective, and political; one that is more loving, more caring and is less possessive and judgmental?" [25]; it could be concluded that it is possible to create a synergy between the development of new biocomposite materials and the protection of the Amazon Rain Forest. This synergy yields a positive impact over the carbon total cycle, reflecting an important contribution for the Global Climate Control.

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