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ORIGINAL PAPER

Biodegradation of Coir and Sisal Applied in the Automotive Industry

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Abstract This paper discusses the results of biodegradability tests of natural fibers used by the automotive industry, namely: coir, coir with latex, and sisal. The biodegradation of coir, coir with latex, and of sisal fibers was determined by monitoring the production of carbon dioxide (CO_2) (IBAMA—E.1.1.2, 1988) and fungal growth (DIN 53739, 1984). The contents of total extractives, lignin, holocellulose, ashes, carbon, nitrogen and hydrogen of the fibers under study were determined in order to ascertain their actual content and to understand the results of the biodegradation tests. The production of CO_2 indicated low biodegradation, i.e., about 10% in mass, for all the materials after 45 days of testing; in other words, no material inhibited glucose degradation. However, the percentage of sisal fiber degradation was fourfold higher than that of coir with latex in the same period of aging. The fungal growth test showed a higher growth rate on sisal fibers, followed by coir without latex. In the case of coir with latex, we believe the fungal growth was not intense, because natural latex produces a bactericide or fungicide for its preservation during bleeding [1]. An evaluation of the materials after 90 days of aging tests revealed breaking of the fibers, particularly sisal and coir without latex, indicating fungal attack and biodegradation processes.

Keywords Biodegradation · Coir · Sisal · Composites · Lignocellulosic fibers

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Introduction

Significant advances have been achieved in the technology of natural fiber composites, which include mixtures of polymers with sisal and coconut fibers.

The main advantaged of vegetal fibers over synthetic fibers are their low density and abrasiveness, low cost, no toxicity, biodegradability, recyclability, their properties of high mechanical strength, the creation of rural employment, their use as reinforcement in various types of plastics, and their excellent thermal and acoustic properties.

Sustainable bio-based eco-products with environmental acceptability that are derived from renewable resources with recycling capabilities and triggered biodegradability [2]. Green polymers [3], also known as bio-polymers [4], are derived from natural/agricultural renewable resources.

Green polymers might in the future reduce our dependency on oil-based polymers.

Commonly, natural fiber reinforced petrol-based polymers are called green composites. The use of green/synthetic polymers, reinforced by either synthetic or natural fibers respectively, will limit the environmental friendliness of the resulting composite because of the low biodegradability and problems related to the materials recycling [5].

In an interesting study, [6] reported that agricultural residues reinforced plastics were subjected, at the end of their life cycle, to a combustion process or landfill, the released amount CO_2 of the fibers is neutral with respect to the assimilated amount during their growth. Wood–plastic composite is very promising and sustainable green material to achieve durability without using toxic chemicals. In comparison to other fibrous materials, plant fibers are in general suitable to reinforce plastics due to relative high strength and stiffness, low cost, low density, low CO_2 emission, biodegradability and annually renewable. Wood–plastic composites are being increasingly used in automotive industries as a result of their superior strength/weight and stiffness/weight ratios.

According to ABRACOCO (Brazilian Coconut Agroindustry Association), coir–latex composites offer various advantages over polyurethane foam, i.e., greater driver comfort (in vehicle seats), excellent aeration, biodegradability, recyclability (e.g., coir vases and car seats), with a cost equivalent to that of foam, thermal comfort, renewability, and combustion devoid of toxic gases. In contrast, foam such as polyurethane is a product that is nonrenewable and can produce toxic gases (hydrocyanic gas) during combustion.

Coir extracted from green coconuts (pygmy coconuts), of which only the milk is consumed, is being used in the production of biodegradable fabrics (geotextiles), which serve as protection against surface erosion caused by the impact and flow of rain, for soil protection and recovery, for erosion control, on steep slopes, as lining in drainage canals and gutters, in landscaping, lawns and gardens. According to DEFLOR—Defesa Florestal Ltda, these products are composed 100% of dehydrated coir interwoven with highly resistant natural adhesives, weighing 300–1,000 g/m^2, which are sold in 2 $\times$ 25 m rolls. The degradation of these fabrics can occur between 24 and 60 months, or even longer. This type of fabric can serve to hold fertilizers and seeds.

One of the applications of coir extracted from the mesocarp of ripe coconuts is in the production of composites for the automotive industry, particularly the manufacture of seats the base of coir with latex for trucks and Class A automobiles, produced by Mercedes Benz (Morassi 1999).[1]

[1] O. J. Morassi (Mercedes Benz do Brasil, São Bernardo do Campo, SP, Brazil, personal communication, 1999).

Seats the base of coir with latex serve as a possible substitute for polyurethane foam seats. The term seat refers to the material that serves as the stuffing of vehicles seats [7]. This option offers a series of advantages, from both the technical and environmental standpoints, since it involves the use of a natural product (coir), thus creating employment for needy populations while at the same time using a product that would otherwise be discarded as waste [7]. Medical studies sponsored by Daimler Benz have indicated that most cases of hemorrhoids occur among truck and taxi drivers who sit of foam seats, because those seats are less aerated and absorb less sweat than coir-latex seats [7].

In view of the increasing use of coir-latex based automotive seats and of sisal composites, it is important to study the biodegradability of these natural fibers, since these products are discarded at the end of their service life. Moreover, the major automakers are increasingly focusing on meeting the *European Community* (*EC*) *2000/53* ELV—"End of Life Vehicles" standard, particularly its article 7, which requires the recycling and/or composting of automotive parts. A more widespread use of natural fibers in vehicles depends on greater recovery and/or recycling, without the alternative of energy burning.

Another natural fiber is sisal, which originates from Mexico's Yucatán Peninsula and whose name derives from a native herb called *Zizal-Xiu*, the same name as the village and port through which the fiber used to be exported to foreign markets [8].

From an anatomical standpoint, sisal fibers are included in the group of fibers called "structural" fibers, whose function is to give the leaves support and stiffness. When extracted, the fibers emerge in the form of bundles with lengths varying from 40 cm to 2 m (average 1.2 m), which are thicker at the base, and have an angular or almost cylindrical section and creamy white coloring [9, 10].

Each fiber is composed of one or more fibrous bundles, each of which, in turn, consists of a large number of juxtaposed cells closely bound by a pectinous substance that does not separate during the manufacturing operations. Because these fibers are thick, rough and stiff, they belong to the category of "hard" or vascular fibers, unlike the group of "soft" or bast fibers (jute, ramie, hemp, flax), which are finer, softer and more flexible [10].

Sisal fibers are extracted from the plant by cutting and defibrating the leaves, followed by washing, drying and cleaning the fibers. In Brazil, the leaves are defibrated in a machine called a "paraibana". Sisal fiber is one of the stiffest vegetal fibers, possessing a high tensile strength. Sisal leaves are composed predominantly of two types of fibers: mechanical fiber and "ribbon" fiber [9]. Their applications are defined according to their characteristics.

The construction sector today also uses sisal-based products, seeking to reduce the use of asbestos for health

reasons. Sisal residues have been used in the manufacture of roof tiles, tanks and dividing walls in various parts of the world [11].

It should be noted that increasing the sisal production in the country not only generates substantial economic results but also contributes decisively to improving the social outlook of a significant portion of the Brazilian population. It is estimated that approximately 800 thousand people's incomes today are directly dependent on the exploitation of sisal [11].

The biodegradation or biotransformation of a material can be defined as a process of chemical modification caused by biological activity under certain conditions of heat, humidity, light, and adequate mineral and organic nutrients. It can also be defined as a process of conversion of a material by microorganisms, carbon dioxide, water, biomass under aerobic conditions, or methane [12, 13]. In this process, if no residual carbon is left, the biodegradation is considered to be total, i.e., mineralization occurred. On the other hand, if there is residual carbon, the process is considered to be one of partial biodegradation or of biotransformation [13]. A method currently under research is biodegradation, especially of polymeric materials, because they are so intensively used and discarded by society. The production of plastics in the US, for example, exceeds 50 million tons a year, and one third of this material is used in the manufacture of purses, raincoats, disposable cups, food trays, packaging, diapers and films for agriculture [14]. The discarding of plastics into the environment has become a problem of major proportions, for plastics occupy a large fraction in volume, i.e., more than 20% of urban waste in the US, although the relative fraction in mass is only 10% [13]. Burning plastic wastes can, in certain cases, produce volatile and toxic materials, as in the case of PVC, whose incineration releases chloric acid (highly toxic and pollutant), dioxins and furans [12]. Recycling alone is not enough to process the enormous quantities of discarded plastics and, in some cases, the final quality of the plastic is not commercially acceptable. Due to technical and financial limitations, recycling is still very restricted, i.e., less than 10% of plastics are recycled today [15].

Many researchers have been dedicated to the development of biodegradable plastics and products, which has required the establishment of criteria to evaluate the products' biodegradability. In addition, reliable and reproducible tests are necessary so that products can be labeled correctly as biodegradable or compostable (Silva 2002).[2]

When new laboratory tests are proposed, a question that often comes up is the ability of the conditions to properly reflect the biodegradability of products in the environment or in a composting plant, for instance. The environments into which materials may be discarded differ significantly in terms of microbial population, pH, temperature, humidity, and pressure, and these characteristics are not reproduced in the laboratory. Another important point is the balance between the storage time required for the product and the demand for rapid degradability.

The literature describes assays to measure the biodegradability of polymeric materials, which are based on the indirect measurement of these materials' degradation by the action of microorganisms as, for example, the microorganisms' consumption of oxygen in the presence of a sample under testing, the quantity of carbon gas produced, or the increase in microbial biomass as a result of the sample's transformation. Any one of these measurements takes into account the ability of microorganisms to decompose the polymeric material, metabolizing it into CO_2, or into biomass through the use of oxygen.

The methods currently employed worldwide to evaluate the biodegradability of polymeric materials include enzymatic methods [16], microbiological methods [17, 18] and the direct soil method [19]. For purposes of comparison, the mass, mechanical properties and molar mass of samples, or even the quantity of degradation products generated, are measured before and after subjecting them to these methods. According to [20], most laboratory tests generally aim to establish a reliable forecast of the biodegradability of substances, products, and liquid and solid wastes in the environment. The trend in the US, European Community and Japan is to test polymeric materials for compostability, given that composting is a widespread form of treatment. In the US alone, about 470 domestic waste composting units have been established each year since 1988. This trend ended up leading to the establishment of the ASTM D-6400-99 *Standard Specification for Compostable Plastics* [21]. In the initial phase, especially when a new material is developed, it is important to establish a faster test than the aforementioned ones to ascertain whether the material can be considered "easily" biodegradable or if it is necessary to evaluate its composition.

Composting and/or biodegradation are environmentally more acceptable alternatives than incineration for the production of energy. Thus, a study was made of the biodegradability of the following materials: coir, coir with latex, and sisal fibers, based on CO_2 production and fungal growth.

Experimental Procedures

Materials

Coir in natura—packaged in 5 kg plastic bags supplied by Biomix (São Paulo, SP, Brazil). Natural coir were removed

[2] L. F. Silva (Biotechnology Group, Chemistry Division, IPT, São Paulo, personal communication, 2002).

from the mesocarp of the fruit, sun-dried and packaged without the addition of latex or any chemical product.

Coir with latex—natural coir were spread out in a rectangular metal pan, latex was applied on them, and the material vulcanized in an oven at 105 °C.

The latex used in the production of coir fabrics was synthetic, i.e., natural latex extracted from the rubber tree (*Hevea brasiliensis*) plus additives, which constitute the so-called "black box" in the composition of synthetic latex.

Sisal fiber—long sisal fibers in 270 kg bales were supplied by the company Sisal Pinheiro (Salvador, BA, Brazil), and cut down to lengths of about 5 cm in a cutting mill at the company Tapetes São Carlos (São Carlos, SP, Brazil).

Elementary Analysis

For the CHN analysis, the fibers were first ground in a Marconi, model 680 mill cutter with a 10 mesh sieve. At least 100 g of each ground material classified as a 40/60 fraction was weighed in a Gehaka model BG 8000 electronic balance. From this mass (100 g), 1–2 mg of each dry material was weighed and subjected to a CHN elementary analysis in duplicate, using a Perkin Elmer, model 2400 CHN elemental analyzer, under the following analytical conditions: combustion temperature: 925 °C and reduction temperature: 640 °C.

Determination of Total Extractives, Lignin and Holocellulose

The samples were ground in a Wiley mill to obtain a fraction of 10, after which they were classified to obtain the 40/60 mesh fraction, which was used for the following chemical analyses, following the cited standards:

1. Preparation of the lignocellulosic fibers for chemical analyses (TAPPI T264 cm-97) [22];
2. Total extractives (ABTCP M 3/69) [23];
3. Klason lignin (TAPPI T222 om-88) [24];
4. Holocellulose: 100 − (% total extractives + % lignin)
5. Cellulose (peroxyacetic acid method—Wright and Wallis) [25]

Biodegradation Test Based on the Production of Carbon Dioxide in an Open System

The methodology utilized was the IBAMA E.1.1.2. (1998) standard [26], which is similar to the ASTM D 5210-92 standard, whereby a dry mass calculated according to the C content of each material is placed in a 4- to 5-L sterile, amber-colored glass flask containing glucose nutrient (75 mg/L). In our study, 136.40 mg of coir, 157.54 mg of coir with latex, and 151.54 mg of sisal were weighed, each of them for 3 L of nutrient solution. The flasks were inoculated with a standard concentration of microorganisms present in soil, corresponding to at least 10^5 colonies per mL.

An air purification system was set up, consisting of six 1-L plastic flasks, each containing 700 mL of NaOH 10 M (to eliminate the presence of CO_2). These flasks were interconnected by appropriate plastic tubes. The initial extremity was connected to a flask filled with dry glass wool (for filtering), which was connected to a compressed air unit. As Fig. 1 indicates, the gas was collected and the production of CO_2 along time was measured at the system's exit, which must be leak free. The CO_2 measurements were taken by titrometry, using 1 molar HCl.

At the end of the test, the percentage of released CO_2 was evaluated and compared with the theoretically predicted values. Any substance whose percentage of released CO_2 reached a minimum of 70% of the theoretical value in a period of 28 days was considered "easily biodegradable". The controls were analyzed concomitantly to the samples' evaluation, namely:

(1a) White: nutrient solution and inoculum.
(2b) Biodegradable standard or positive control: nutrient solution, inoculum and a standard substance known to be biodegradable, at PA glucose.
(3c) Test substance: nutrient solution, inoculum and the substance or material to be tested.
(4d) Inhibition of the test substance or negative control: nutrient solution, inoculum, biodegradable standard, and the test substance. The purpose of the negative control is to ascertain the existence or absence of the inhibitory effect of the sample under study on the biodegradation of glucose.

Resistance of Fungi and Bacteria

The methodology employed was adapted from the A, B, B′ methods of the DIN 53739 (1984) standard [27], based on the ISO 846 (1978) standard. The test consisted of exposing test specimens of the tested samples to the action of the fungi listed in Table 1. The test specimens were prepared by cutting several natural fibers into 3-cm lengths, grouping them together to form a 3 × 3 cm square, i.e., 9 cm^2.

The inoculum was prepared from a separate culture of each fungus on a Petri dish containing the solid medium indicated in the standard. After the fungus's growth in an incubator at 25 °C, the spores were collected and agar residues were removed. A suspension was prepared from each culture until a concentration of 10^6 spores/mL was

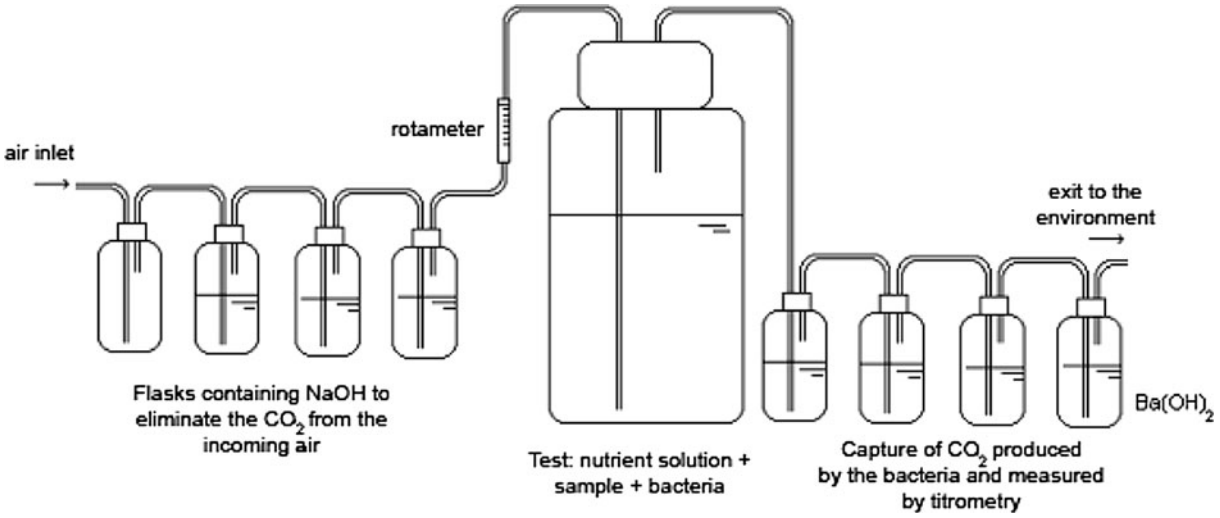

Fig. 1 Schematic diagram of the biodegradability test based on the measurement of CO_2 formed in an open system

Table 1 Reference microorganisms recommended by the DIN 53739, 1984 standard

CCT[a]	Microorganism	Reference	Medium	Temperature (°C)
4458	*Aspergillus niger*	ATCC′ 6275	MEA (1)	25
1208	*Penicillium funiculosum*	IMI″ 114933	MEA	25
1211	*Gliocladium virens*	ATCC 9645	PCA (2)	25
1219	*Chaetomium globosum*	ATCC 6205	OA (3)	25
1209	*Paecilomyces variotti*	ATCC 16023	MEA	25

(1) malt extract-based medium, (2) carrot and potato-based médium, and (3) oat-based medium

[a] Collection of tropical cultures 'American type culture collection' "International Mycological Institute"

reached. Equal volumes of the different species were mixed and used to inoculate the test specimens. The results were classified according to the criteria presented in Tables 2 and 3.

Results and Discussion

CHN Elementary Analysis

Table 4 shows the average results and their respective estimates of the standard deviation from the C, H and N contents, as well as the C/N relation of the materials under study. The values of the C/N relation can be considered high, i.e., about 200, with the sample of coir showing the lowest value, followed by the coir with latex and the sisal samples. This relation may justify the low attack/biodegradation that occurred.

The ideal C/N relation for the beginning of biodegradation in a composting system is 30/1, i.e., the microorganisms more easily attack materials with a C/N close to 30, while the degradation of materials with a higher C/N relation is slower [28].

Determination of Total Extractives, Lignin and Holocellulose

The results of the determination of contents of total extractives, lignin, holocellulose, cellulose, hemicellulose and ashes are shown in Table 5.

The results shown in Table 5 indicate that, on average, sisal contains 7% of lignin and 84% of holocellulose, while coir has 31% of lignin and 66% of holocellulose, which

Table 2 Classification of fungal growth intensity

Intensity of growth	Evaluation
0	No visible growth under microscopic examination
1	No growth visible to the naked eye, but visible under the microscope
2	Growth visible to the naked eye, 25% of the sample's surface covered
3	Growth visible to the naked eye, 50% of the sample's surface covered
4	Considerable growth, more than 50% of the sample's surface covered
5	Intense growth over the entire surface of the sample

Table 3 Interpretation of the classification of fungal growth intensity

Method	Intensity of growth	Evolution of the sample on the material
A	0	The material is not a nutritive medium for the microorganisms, i.e., it is inert or fungistatic
	1	The material contains nutritive substance or is contaminated, allowing for a biased growth
	2 or 3	The material does not resist fungal attack and contains nutritive substance that can lead to the development of microorganisms
B or B′	0	Marked fungistatic action
	0 + inhibition zone	Marked fungistatic action, extending through the zone surrounding the sample
	1	The material is not completely fungistatic
	2–5	Fungistatic action tending toward zero

Table 4 CHN elemental analysis of the materials under study

Material	Carbon (%)	Hydrogen (%)	Nitrogen (%)	C/N Relation
Sisal fiber	42.09 ± 0.02	5.8 ± 0.1	0.18 ± 0.04	233.8
Coconut fiber *in natura*	45.43 ± 0.06	5.8 ± 0.2	0.21 ± 0.02	216.3
Coconut fiber with latex	45.1 ± 0.2	6.3 ± 0.1	0.21 ± 0.04	214.8

Table 5 Determination of total extractives, lignin, holocellulose and ashes, without correction of the ash content

Material	Total extractives (%)	Lignin (%)	Holocellulose (%)	Cellulose (%)	Hemicellulose (%)	Ashes (%)
Coconut fiber	2.3 ± 0.8	31.8 ± 0.1	65.8 ± 0.7	45.5 ± 0.4	20.4 ± 0.4	1.34 ± 0.04
Coconut fiber/latex	3.1 ± 0.1	51.0 ± 0.7	45.9 ± 0.6	32.9 ± 0.6	13.1 ± 0.2	6.04 ± 0.12
Sisal fiber	9.3 ± 0.6	7.0 ± 0.1	83.8 ± 0.7	59.2 ± 0.4	24.6 ± 0.6	1.95 ± 0.02

Holocellulose cellulose + hemicellulose

explains the faster degradation of sisal fibers in our laboratory tests, since holocellulose is composed of polysaccharides, cellulose and hemicelluloses, which are more readily degradable substances.

The variation in the results of the lignin and holocellulose for the coir with latex can be explained by the fact that, during the determination, the coir was not completely dissolved by the sulfuric acid. Therefore, the mass of this composite interfered in the determination of its lignin and holocellulose content.

Lignin is degraded initially by enzymes that are extracellular from the smaller molecules, which are partially metabolized by microorganisms and then converted into phenols and quinones [29].

Biodegradation Test by Production of Carbon Dioxide in an Open System

The CO_2 values were calculated from the HCl volumes used in the titration of the flasks containing $Ba(OH)_2$ and the results of this experiments demonstrated a glucose biodegradation rate of about 79% (Fig. 2a) after 4 days of culture. After 11 days of culture, the biodegradation had already exceeded 97%, evidencing the activity of the assay, i.e., the medium degraded the glucose during the test.

The coir sample showed a biodegradation rate of about 10% after 38 days of testing, indicating no significant alterations occurred during the 45-day test and demonstrating that this material is difficult to degrade when compared with glucose. On the other hand, this material did not inhibit glucose degradation, since it was found that after 161 h, 96% of the glucose and CO_2 had degraded (Fig. 2a).

Figure 2b shows the values of CO_2 production of the coir-latex composite. The biodegradability results of this composite material showed a biodegradability rate of less than 10%, even after 47 days of testing, demonstrating that this material is hard to degrade. However, this material did not inhibit the degradation of glucose (Fig. 2b).

Figure 2c depicts the values of CO_2 production of the sisal sample. A biodegradability rate of less than 10% was found, even after 47 days of testing, demonstrating that this

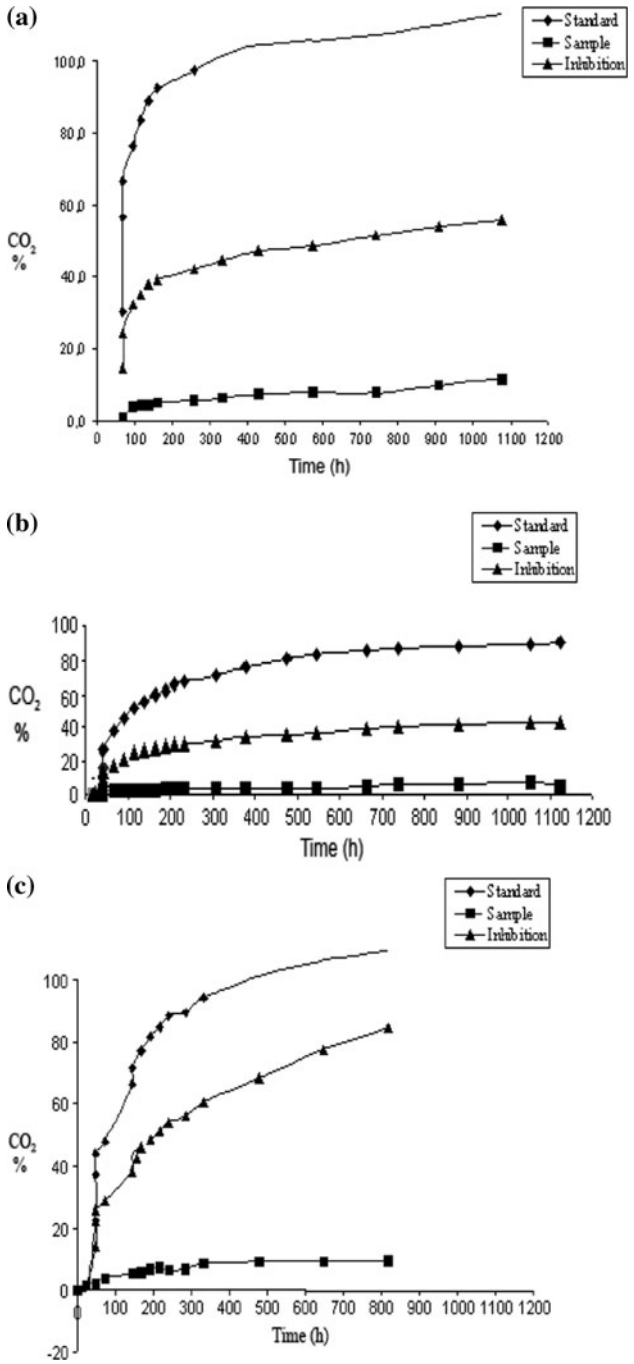

Fig. 2 Percentage of CO_2 formed by the sample of: **a** coir, **b** coir with latex, **c** sisal fiber

material is also difficult to degrade. Even so, this material, too, did not inhibit the degradation of glucose (Fig. 2c).

Comparing the percentage of degradation of sisal fiber against that of coir with latex, the former displayed a higher degradation rate over the same aging period.

It should be noted that, for the application of coir with latex in vehicle seats, the results obtained in this research may indicate slow biodegradation under laboratory

Table 6 Visual evaluation of the intensity of fungal growth at 14 days of testing for each sample of fiber under study

Culture medium	Method/ lot	Dish (no.)	Intensity of fungal growth[a]		
			Coconut fiber	Coconut fiber with latex	Sisal
IM	A/I	1	1	1	$4^{(F)}$
IM	A/I	2	1	1	4
IM	A/I	3	1	1	$4^{(F)}$
IM	A/I	4	$1^{(F)}$	1	4
IM	A/I	5	$1^{(F)}$	$1^{(F)}$	4
IM	A/S	1	3	0	$1^{(F)}$
IM	A/S	2	0	$0^{(F)}$	1
IM	A/S	3	$0^{(F)}$	$0^{(F)}$	1
IM	A/S	4	$4^{(F)}$	0	1
IM	A/S	5	$2^{(F)}$	0	$1^{(F)}$
CM	B/I	1	$1^{(F)}$	$1^{(F)}$	$4^{(F)}$
CM	B/I	2	$4^{(F)}$	1	4
CM	B/I	3	2	$1^{(F)}$	4
CM	B/I	4	3	0	$3^{(F)}$
CM	B/I	5	1	0	4
CM	B/S	1	0	$1^{(F)}$	$4^{(F)}$
CM	B/S	2	$0^{(F)}$	1	$4^{(F)}$
CM	B/S	3	$0^{(F)}$	$1^{(F)}$	$4^{(F)}$
CM	B/S	4	$4^{(F)}$	0	$4^{(F)}$
CM	B/S	5	0	0	3
CM	B′/I	1	1	0	$4^{(F)}$
CM	B′/I	2	1	0	$5^{(F)}$
CM	B′/I	3	$3^{(F)}$	$0^{(F)}$	3
CM	B′/I	4	1	$0^{(F)}$	3
CM	B′/I	5	1	0	3
CM	B′/S	1	$5^{(F)}$	0	$4^{(F)}$
CM	B′/S	2	5	0	4
CM	B′/S	3	4	$0^{(F)}$	$4^{(F)}$
CM	B′/S	4	5	$0^{(F)}$	$4^{(F)}$
CM	B′/S	5	$5^{(F)}$	0	4
Without medium	B'/I_2	1	0	0	0
Without medium	B'/I_2	2	$0^{(F)}$	$0^{(F)}$	0
Without medium	B'/I_2	3	0	0	$1^{(F)}$
Without medium	B'/I_2	4	0	0	0
Without medium	B'/I_2	5	0	0	0

IM incomplete medium, *CM* complete medium

[a] Intensity of Fungal Growth evaluated according to Table 6 of the DIN 53739, 1984 standard

(F) Petri dish photographed under a Leica model MZ8 stereoscopic microscope

conditions, signifying their longer service life. However, it does not characterize them as nondegradable. A biodegradation study using more specific microorganisms for the degradation of lignin and cellulose in a composting system is necessary for the fibers under study here.

The composite is a stable product resulting from the microbial decomposition of organic materials that are converted into humus, carbon dioxide and heat. The biodegradation of lignin is the key activity during composting, due to its involvement in the humidification and release of nutrients for microorganisms. This polymer is difficult to degrade and reduces the availability of other organic constituents, although this effect is, to a large extent, a physical restriction, with molecules reducing the surface area available for enzymatic activity and penetration [29]. However, it is assumed that humus is formed mainly from lignin [29] via a very complex chemical pathway involving degradation and condensation reactions. Lignin degrades initially by enzymes that are extracellular to small molecules, which are partially metabolized by microorganisms, after which they are converted into phenols and quinones. All these degraded lignin fractions are then polymerized by a free radical mechanism to generate humus [29].

Fig. 3 Photomicrographs illustrating the coconut fiber without inoculum and after 14 days of fungal growth (× 13 magnification): **a** without inoculum, **b** IM AS method, **c** IM AI method, **d** CM BS method, **e** CM BI method, and **f** CM B′S method

Resistance of Fungi and Bacteria

Following the DIN 53739, 1984 standard [27], the samples exposed to lots I and S in terms of fungal growth (according to criteria presented in Table 2) were first visually examined by the naked eye and then, when necessary, under a stereoscopic microscope. To interpret and reach conclusions about the fungal attack on the materials under study, the results of the visual examination were interpreted according to the criteria listed in Table 3.

The results of the visual examination of the intensity of fungal growth after 14 days of testing of each sample under study are shown in Table 6. A comparison of these results indicated that sisal was the material most profusely covered with fungal growth.

After photographing the intensity of fungal growth on the materials in question at 14 and 28 days, an evaluation was made of each sample at 90 days by lifting the material with a pair of pincers from the laminar flow to check if breakup of the fibers had occurred, whenever this was found to have occurred, the material was photographed in a stereoscopic microscope. The main photographs, both of the intensity of fungal growth and breakup of the materials, are depicted in Figs. 3, 4, 5, 6.

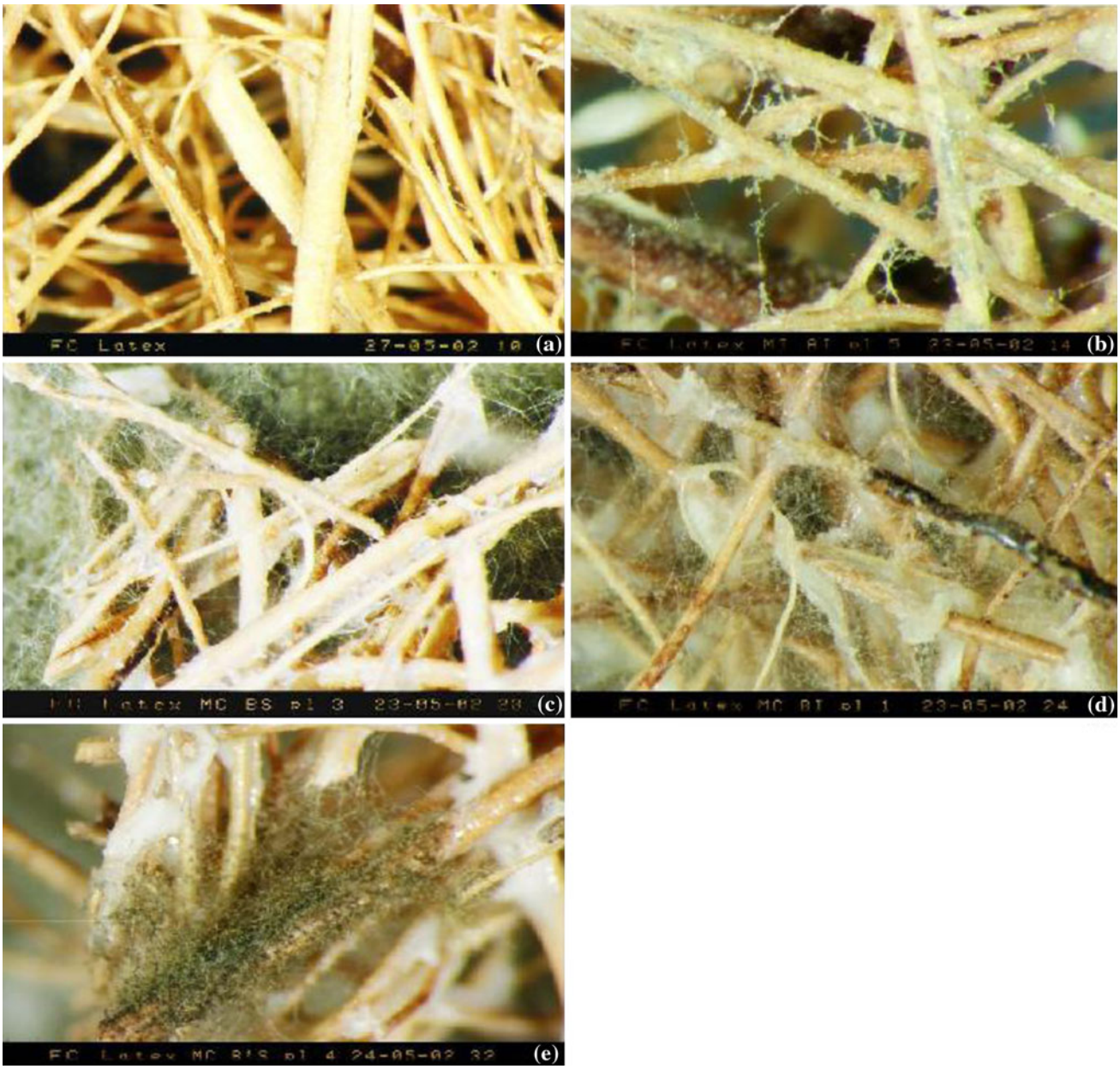

Fig. 4 Photomicrographs illustrating the coconut fiber with latex, without inoculum and after 14 days of fungal growth (× 13 magnification): **a** without inoculum, **b** IM AI method, **c** CM BS method, **d** CM BI method, and **e** CM B′S method

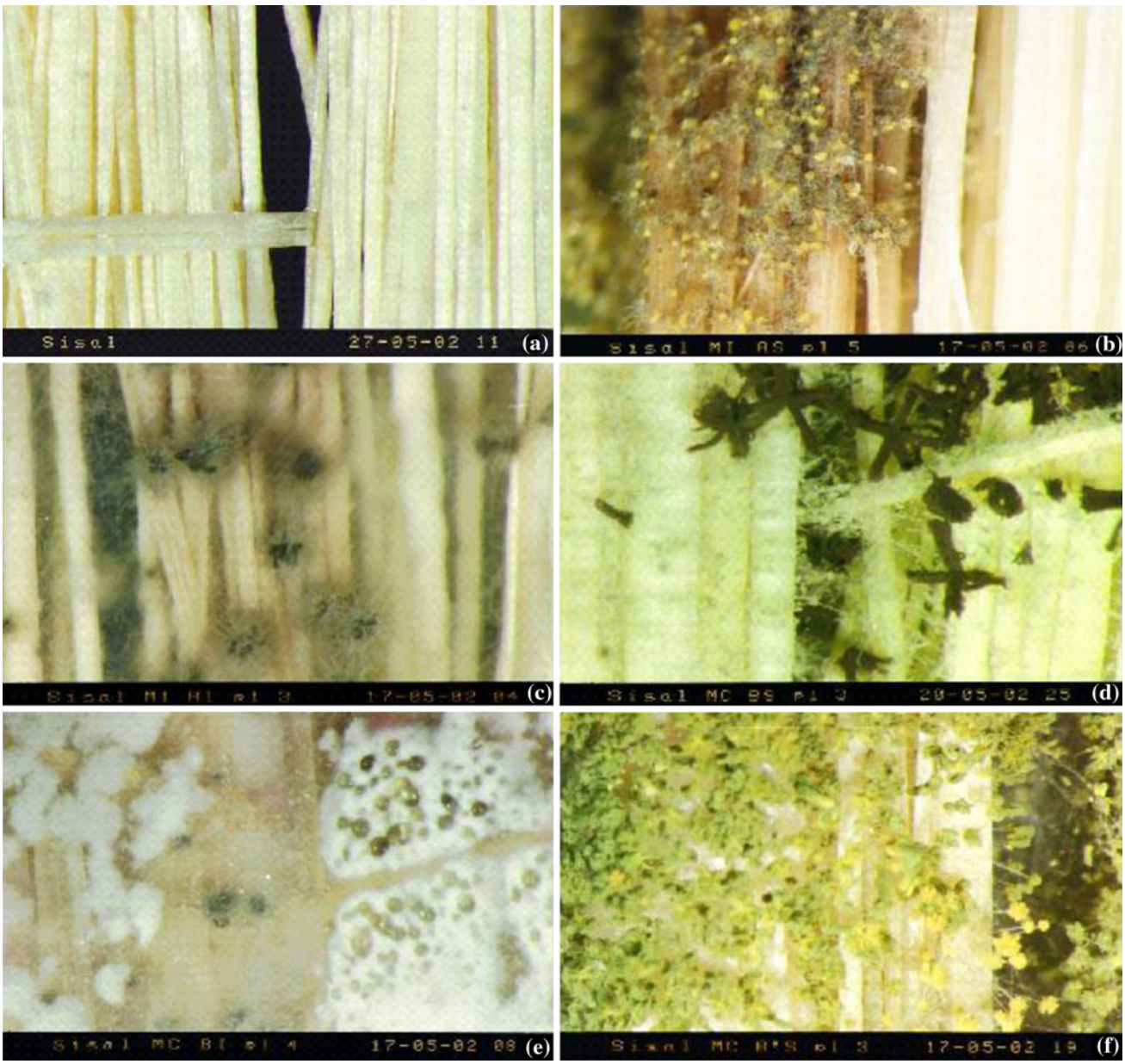

Fig. 5 Photomicrographs illustrating the sisal fiber, without inoculum and after 14 days of fungal growth (× 13 magnification): **a** without inoculum, **b** IM AS method, **c** IM AI method, **d** CM BS method, **e** CM BI method, and **f** CM B′S method

Figures 3, 4, 5, 6 indicate that sisal was the material most densely covered with fungal growth, followed by coir without latex. If is believed that, in the case of coir with latex, fungal growth was not as intense as on the other materials because latex, when it is bled from the tree, produces a preserving bactericide and/or fungicide [1].

Conclusions

With regard to the biodegradability test based on the measurement of carbon dioxide released in an open system, all the materials under study showed a biodegradation rate of approximately 10% after about 45 days of testing, indicating that these materials do not degrade easily. On the other hand, none of the materials inhibited the degradation of glucose. However, comparing the materials, sisal fiber degradation was found to be greater than that of the other materials over the same aging period. The lignin, cellulose and hemicellulose contents explain the faster degradation of sisal fiber. The test of the activity of selected fungi strains clearly showed that the greatest fungal growth also occurred on sisal, followed by coir without latex. We believe that coir with latex did not show intense fungal growth because natural latex

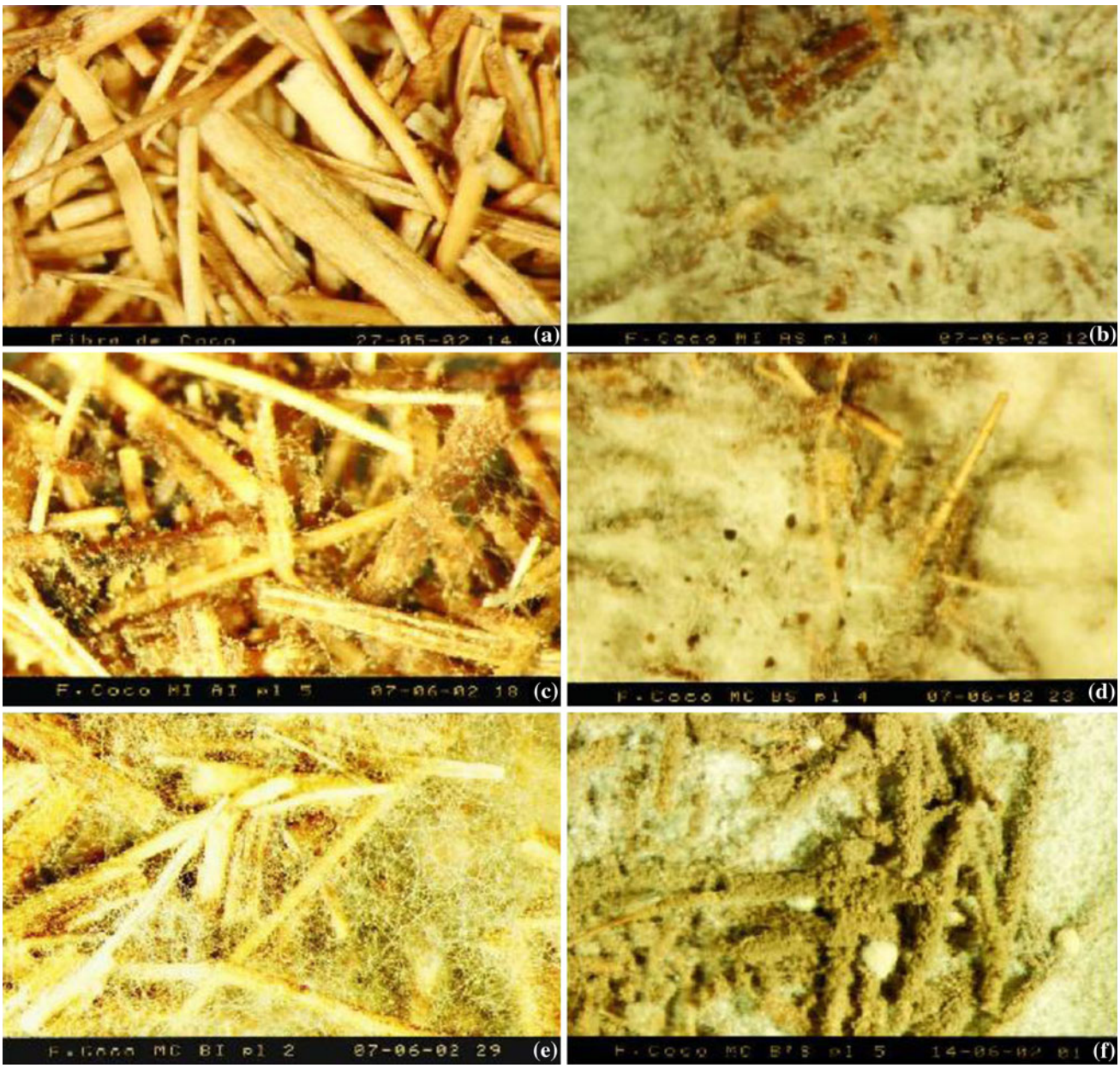

Fig. 6 Photomicrographs illustrating the coconut fiber, without inoculum and after 28 days of fungal growth (× 21 magnification): **a** without inoculum, **b** IM AS method, **c** IM AI method, **d** CM BS method, **e** CM BI method, and **f** CM B′S method

contains a bactericide and/or fungicide for its preservation during bleeding.

The results of this study regarding the biodegradation of these natural fibers reveal that they are difficult to degrade, which is an excellent fact from the standpoint of their application in the automotive industry, leading to a longer product service life. This study allows us to state that it is possible to meet the requirements of the European standard ELV—"End of Life Vehicles", Directive 2000/53 EC (European Community), Article 7, which requires the recycling and/or composting of automotive parts, and forbids their incineration. A more widespread use of natural fibers in vehicles depends on a greater recovery and/or recycling without the alternative of burning. Composting and/or biodegradation are environmentally more acceptable alternatives than incineration.

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