

Article

Durability Evaluation of New Composite Materials for the Construction of Beehives

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Abstract: Given the current situation we face regarding climate change, one of the greatest and most critical concerns is related to the reduction in the bee population. This population largely depends on beekeeping production units around the world. However, these production units also face great challenges in the construction of beehives, as pine wood generally deteriorates within a period of five years or less. This relatively rapid deterioration has both economic and environmental repercussions, which may affect the economic sustainability of the beekeeping system. The objective of this research was the production and subsequent evaluation of the durability of alternative composite materials that can be used in beehive construction. The materials are based on high-density polyethylene and agro-industrial residues (fique fiber, banana fiber, and goose feathers) from the Boyacá region of Colombia. The composite materials studied in the present study were exposed to xylophagous fungi for 90 days, at constant humidity and under controlled temperature conditions that are conducive to fungi proliferation. The results showed that composite materials that include fique fibers are the most promising substitute for wood in the construction of beehives. Indeed, these materials were shown to be 80% more resistant to pathogen attack and durable weight loss than pine wood. These durability results may be of great importance for future implementation in beekeeping production units. They have the potential to impact not only the sustainable development of rural communities, but also to make a great ecological contribution by reducing the need to cut down trees while maintaining the health of beehives.

Keywords: new materials; sustainable beehives; xylophagous fungi; sustainable development; apiculture



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1. Introduction

Beekeeping is an agro-industrial activity that consists of raising, caring for, and exploiting bees [1]. Different marketable products are derived from this activity, such as honey, pollen, wax, propolis, and royal jelly, among others [2]. In addition to the socioeconomic aspects, beekeeping is of great importance at the environmental level due to its contribution to ecological conservation and biodiversity [3]. Said contribution to the ecosystems is directly linked to the activity of its main actors, namely bees, in nature [4]. These insects function as pollinating agents; that is, they are insects that, when searching for their food, travel between plant flowers, exchanging pollen between them, thus favoring the reproduction of the flora [5].

According to data from the Food and Agriculture Organization (FAO), world beekeeping exhibited an average annual growth of 1.7% in the period between 1990 and 2016 [6].

However, even though beekeeping is a beneficial activity that generates benefits both economically and environmentally, it faces great challenges regarding the quality of its processes, development, and sustainability. One of these challenges is resistance, which principally concerns the conservation and maintenance of hives.

A hive is the site occupied by a colony of bees. Inside each hive, the bees organize themselves in a hierarchical order, with each of its members having defined functions [7]. In productive beekeeping, man-made hives are used in order to sustain and increase the biological activity of bee colonies [5,8]. Since ancient times, wood has been used as the base material for the manufacture of these structures [9]. As a result, it is common to find hives made of carefully cut and planed dry wood [10,11]. However, from environmental and economic perspectives, wood is a resource that is not sustainable. This is due to its low durability and the accelerated degradation of the wood, which is caused by environmental conditions and the attack of pathogens [11,12].

The most common pathogenic attack on the structure of the wood used in hives is a result of xylophagous fungi [13–16]. These fungi feed on cellulose and lignin, the basic components of wood, which leaves the wood in a state of rot due to degradation, thus reducing its physical, structural, and mechanical properties [17]. There are three currently known types of wood decomposition caused by xylophagous fungi: white rot, brown rot, and soft rot [18]. White rot is the most common type of wood degradation that occurs in beekeeping. It causes the lignin and cellulose present in the wood to degrade at a faster rate than that which occurs when brown or soft rot fungi are present [19,20]. Fungi of this type reproduce rapidly in environments that contain 20% or less humidity, decreasing and deteriorating the resistance of the wood in the hives by up to 50% in six months [13]. Consequently, beekeepers face additional costs in their production processes, as they must either change the hive, or purchase wood treated with fungicidal chemical compounds—advanced formula products for the treatment of xylophagous fungi [21]. Thus, there is a need for the wood used as a raw material in beehive construction to be replaced or reduced. This may in turn reduce the amount of tree felling and investment cost overruns, as well as increase the economic potential of this agro-industrial activity, generating a source of income for the people working in the industry.

In recent years, scientists have investigated the concept of increasing the value of agro-industrial waste so that biomaterials can be produced that can be integrated into traditional production units. As a result, sustainable development can be generated in the agricultural sector [22]. Agro-industrial residues have a complex structure and composition which are based on the combination of polysaccharides, proteins, carbohydrates, etc. These properties offer the possibility of using waste as renewable natural resources, so that they become low-cost eco-materials, which are easily accessible, friendly to the environment, and sustainable from an environmental, economic, and social perspective [23]. The properties of a material influence the durability of the final product, so material selection must include factors such as the economic costs that result from pollution and energy expenditure, in addition to social factors linked to the specific production methods [24]. Agriculture is an important productive sector in Colombia, in which large volumes of agro-industrial residues are generated. Thus, it is important to consider the application of the concept of a circular economy in the apiculture sector. This may allow us to improve the sustainability of production units by repurposing the waste from other production units.

Considering the problems discussed above, there is a need to generate alternatives that allow us to increase the economic sustainability of hives, while avoiding any negative interference with the biological processes of the bee colonies [25]. As durability is one of the most important factors in beehive construction and purchase [26], various materials have been considered as potential wood substitutes, including plastics, concrete, ceramics, and plant fibers [27], with all of these being continuously evaluated.

Consequently, the main research question that arises in the context of the present study is, ‘What is the optimal eco-material that can be used as a full or partial replacement for wood in the construction of beekeeping hives?’ Thus, the objective of this study is to

evaluate the durability of new composite materials with natural fibers in the construction of hives, based on their resistance to pathogens. These new composite materials will be subject to biological degradation caused by xylophagous fungi that have been isolated from different hives in the municipalities of Paipa, Pachavita, and Duitama Paramo Pan de Azucar) in the Department of Boyaca, Colombia.

2. Materials and Methods

In order for the present research to be conducted, the pathogenic fungi that affect the apiaries in the field had to be extracted, and the composite materials had to be developed with the dimensions described below.

2.1. Obtaining Xylophagous Fungi from the Study Areas

Following the Occupational Health and Safety (OHS) protocols in beekeeping [28], the xylophagous fungi were obtained from beehives located in the municipalities of Paipa, Pachavita, and Duitama (Paramo Pan de Azucar). In this way, it was possible to obtain wood degrading agents from the same study cases. The presence of xylophagous fungi was established by taking samples from five hives in the Paipa and Duitama apiaries, using a scalpel sterilized with ethyl alcohol. These samples were then deposited in humidity chambers, each chamber consisting of a glass container and absorbent paper moistened with distilled water. The humidity chambers were kept in the laboratory for two weeks in order to stimulate the growth and sporulation of the fungus.

2.2. Isolation of Xylophagous Fungi in the Laboratory

First, a macroscopic observation of the samples was carried out in an OLYMPUS Center Valley, PA, USA, brand stereoscope. To do this, with the help of simple dissection forceps, the wrapper was removed from the glass container, and a piece of wood was placed in a Petri dish. The Petri dish was then placed on the stage of the stereoscope, securing it with the clamps allowing for the macroscopic observation of the fungus to be conducted and photographs to be taken. Second, the transfer of each of the samples to humidity chambers was carried out. To do this, with the help of simple dissection forceps, previously sterilized with ethyl alcohol (C_2H_5OH), both the sample and wet paper were removed from the glass container. The glass container was dried with absorbent paper, and the piece of wood was wrapped in another strip of previously moistened absorbent paper. The wrapper was then reintroduced into the glass container. Third, the mycological staining method was used in order to observe the morphology of each fungus under the microscope. To do this, with simple dissection forceps, the sample was removed from the humid chamber and placed on a slide; then, a piece of adhesive tape was superficially adhered to the sample in order to obtain a portion of the fungus while retaining its structure, with the tape being immediately removed from the sample. After that, in order to identify the xylophagous fungus, a drop of lactophenol blue was added to a clean slide before adhering the tape with the sample onto the slide, allowing for it to be visualized through the microscope. A photographic record of what was observed under the microscope was also made. Finally, the fungi were planted in Petri dishes with PDA agar (Potato Dextrose Agar) for 24 h at 35 ± 0.5 °C in a MEMMERT incubator, Model IN 55. Finally, several replicates of the seeding process were made, until a 100% pure isolated fungus culture was obtained. At the end of the test, five xylophagous fungi of the genus *Fusarium* sp. were isolated.

2.3. Obtaining the Composite Material for the Hive

Composite materials based on high-density polyethylene and agro-industrial waste were obtained. Virgin high-density polyethylene (HDPEv), purchased in the form of granules from the MARLEX company The Woodlands, TX, USA, was selected. It was chosen for the blown film grade of HDPE, which has high molecular weight, better processability, and excellent mechanical properties. Its fluidity index is 0.09 g/10 min, and its density is 0.953 g/cm^3 at a temperature of 230 °C. It is widely used to make pipes for the distribution

of drinking water, food containers, detergents, and other chemical products, thus ensuring that it is safe for use in hives.

Agro-industrial residues (natural fibers from bananas, fique, and goose feathers) from the Boyacá department were selected for their use in the reinforcement of the composite material, as they may be beneficial in increasing the tensile strength of the polymeric matrix. For the experimental work, the banana and fique fibers were cut separately, by hand, to an average length of 5–6 mm. The cut fibers were then immersed in 5% NaOH for 12 h and subsequently washed with distilled water. Additionally, the fiber was bleached with 30% hydrogen peroxide, washed again with distilled water, and dried in sunlight in order to remove impurities from the surface of the fiber. A sieving process was carried out using a 1.0 mm sieve in order to obtain fiber uniformity after the drying process was complete. Finally, the fibers were dried in a BIOBASE model BOV-VF series forced-air drying oven at a temperature of 80 °C for 5 h in order to remove moisture before being vacuum packed for further processing. The goose feathers were collected from the municipality of Duitama, cut to an average length of 5–6 mm, and subjected to a 2% alkaline treatment for 4 h. They were then washed with distilled water and dried in sunlight before being processed in the drying oven at 70 °C for 5 h.

2.4. *Manufacture of Specimens for Material Degradability Tests*

The molding process was carried out using a hot press. An extrusion process was utilized in order to mix the polymer and fibers, allowing for a better distribution of the fiber within the polymeric matrix. Three different materials with different natural fiber reinforcements (banana, fique, and goose feathers) were created with two different weight percentages (10% and 15%). These materials were then fed through a hopper and mixed at a speed of 50 rpm and a temperature of 170 °C. Composite filaments were obtained from the extruder and passed through cold water. The fibers were made into pellets, with an average length of between 4 and 5 mm in length, using a pelletizer. These granules were then kept in a hot air oven at 90 °C for 5 h in order to remove moisture. After this, the granules were submitted to the hot-press process in a 18 cm × 14 cm mold, with 80 g of composite material added. Finally, the pressing process was conducted at a temperature of 170 °C, until a thickness of 3 mm was reached. The composite material was then allowed to cool for 2 h.

Finally, a plate was made by means of the hot-pressing process for each composite material for use in the main degradation test using xylophagous fungi. When the process was complete, the six composite material samples were cut by laser. The wood samples were cut by a saw to the dimensions of 2.5 cm × 2.5 cm × 0.3 cm. Each of the samples was dried at 80 °C for 2 h in order to remove all traces of moisture. After this, the initial weight was recorded to determine the percentage of degradation that the material suffered due to the subsequent growth of the xylophagous fungi.

It should be noted that in addition to the pinewood and the developed composite materials of virgin reinforced high-density polyethylene (HDPEv) with natural fibers, the recycled plastic, which is composed of polyethylene, polypropylene, and polyvinylchloride, was also analyzed. All these recycled materials have been used in the construction of beehives, with a high degree of acceptance by the bees.

2.5. *Fungal Growth Degradation Test*

Laboratory Procedure for Composite Material Degradation

First, a nomenclature was assigned to each of the composite materials for subsequent degradation testing using xylophagous fungi (Table 1). For each material, 16 replicas were obtained, 3 for each isolated xylophagous fungus. In order to determine the natural durability of the developed materials, the ASTM D 2017 standard was used as a reference: "Standard test method for accelerated laboratory test of resistance to natural decomposition of wood." This standard was utilized in order to have a reference for the pine wood that is currently used.

Table 1. Nomenclature of the materials to be evaluated.

Nomenclature	Material Type
A	10% Plantain Fiber-Reinforced HDPE
B	15% Plantain Fiber-Reinforced HDPE
C	10% Goose Feather Fiber-Reinforced HDPE
D	15% Goose Feather Fiber-Reinforced HDPE
E	10% Figue Fiber-Reinforced HDPE
F	15% Figue Fiber-Reinforced HDPE
G	Pinewood (Control Material)
H	Recycled Plastic

The degradation test began with the drying of the samples. For this, the specimens were dried to a constant weight at 80 °C in a drying oven C. Then, the specimens were subjected to an immersion treatment in distilled water for 72 h in order to provide them with adequate humidity for fungal growth. Finally, the test tubes were sterilized in an autoclave ADVANCE 18L to eliminate any other microorganism that could alter the results.

At the same time, the isolated xylophagous fungi were replicated in a 2% Malt Extract Agar (EMA) culture medium in Petri dishes for 8 days at a temperature of 27 °C. This was done in order to achieve a total coverage of the Petri dish with the mycelium of the fungus. The test tubes of the sterilized composite materials were aseptically placed on the mycelium developed in the Petri dishes. All these procedures were developed in the laminar flow chamber TOPAIR Systems Model HC-H120P. Afterwards, the Petri dishes were incubated for a period of 90 days at 27 °C for a period of 90 days at 27%. The entire experimental procedure was carried out in the laboratories of Santo Tomás University in Tunja, Colombia.

2.6. Calculation of the Degradation of the Composite Material

At the end of the test, the specimens were cleaned of all traces of mycelial tissue and subsequently dried in an 80 °C oven until a constant weight was reached, thus determining the final dry weight. The percentage of consumption or weight loss of the wood due to rotting was determined using the following equation:

$$\%C = \frac{PSi - PSf}{PSi} \times 100\% \quad (1)$$

Equation (1). Consumption or weight loss, shown as a percentage, where: %C is the consumption or weight loss in a percentage, *PSi* is the initial dry weight, and *PSf* is the final dry weight.

The %C values were interpreted according to the ASTM D 2017 standard to obtain the classification of the species according to their natural durability, as shown in Table 2.

Table 2. Classification of wood according to its biological resistance.

Average Weight Loss (%)	Degree of Resistance to the Xylophagous Fungus	Classification
0–10	Highly Resistant	A
11–24	Resistant	B
25–44	Moderately Resistant	C
45 a mas	Not Resistant	D

Source: ASTM D 2017 [29]. Esta Tabla Fue Adaptada Del Estudio DE José L. Claros Cuadrado (2017).

Finally, a statistical analysis was carried out in order to identify significant differences between the weight loss of the composite materials, as well as between the fungi, to determine if they exhibit the same degrading behavior toward the composite materials.

3. Results

Figure 1 shows the images of the fungi collected in the apiaries and their proliferation.

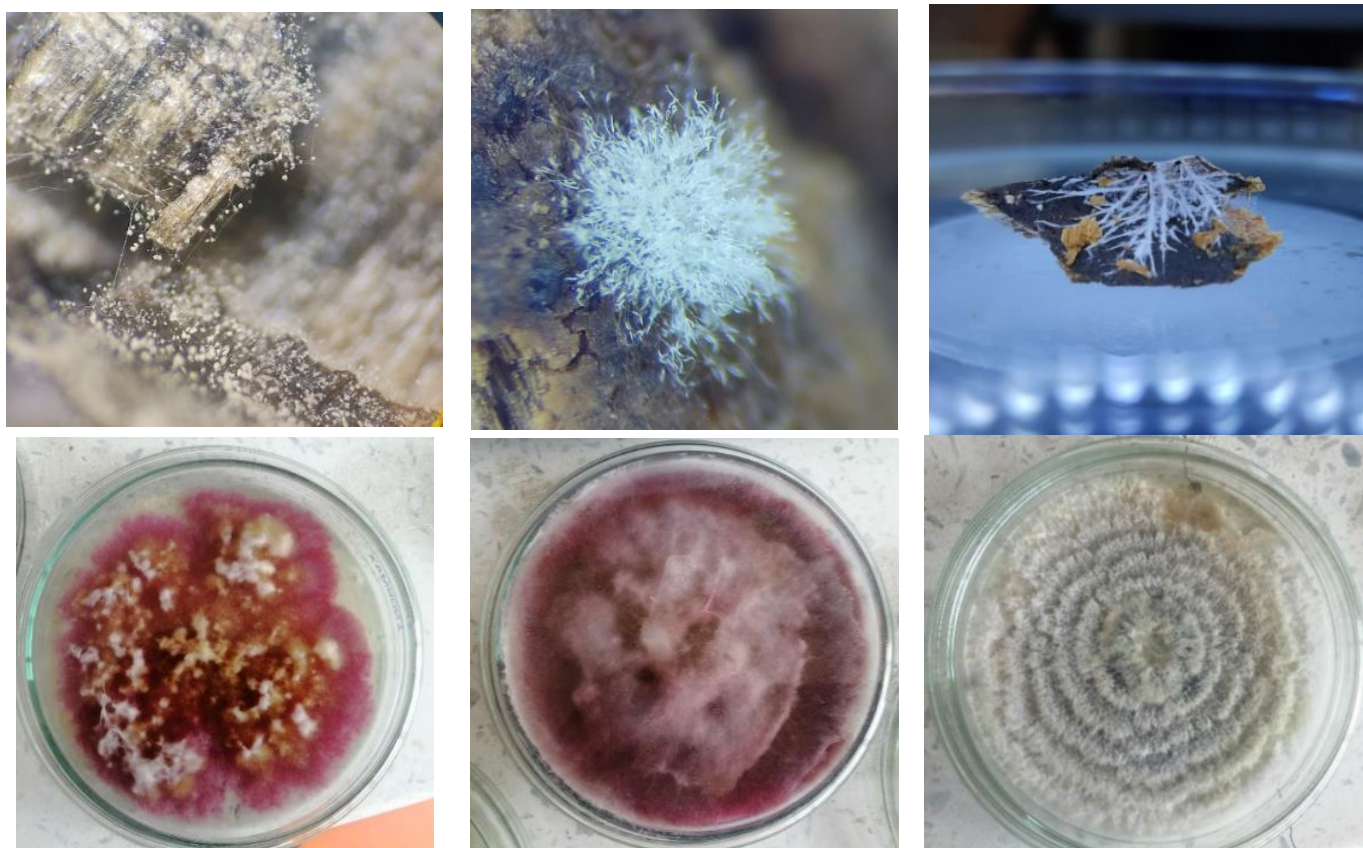


Figure 1. Xylophagous fungi observed in the stereoscope before and after their isolation.

Figure 2 shows the average weight loss that the three replicas of each of the eight materials suffered during the 90-day period of exposure to the destructive action of the xylophagous fungi. An analysis of variance with a factorial design demonstrated that there was no significant difference between the xylophagous fungi ($p = 0.160$). However, there was a highly significant difference between the composite materials ($p = 0.000$). These experimental results are shown in Table 3, where the average weight loss of each material is presented. Our results confirmed that the five isolated specimens of xylophagous fungi behaved similarly in all the composite materials, with wood suffering the highest levels of degradation, and recycled plastic suffering the lowest. These results validate the isolation procedure of xylophagous fungi for the material degradation test.

Of the different materials studied, the material reinforced with 10% goose feathers, the material reinforced with 10% fique fiber, and the material reinforced with 15% fique fiber are the most promising with regards to increasing the degree of hive durability. These three materials registered the least weight loss, despite the action of the xylophagous fungi. Materials containing fique fiber increase the durability parameter, despite the fact that the fiber, being a plant material based on lignin and cellulose, could be susceptible to attack by xylophagous fungi over time.

Figure 3 shows the proliferation of xylophagous fungi in the materials evaluated by time of exposure.

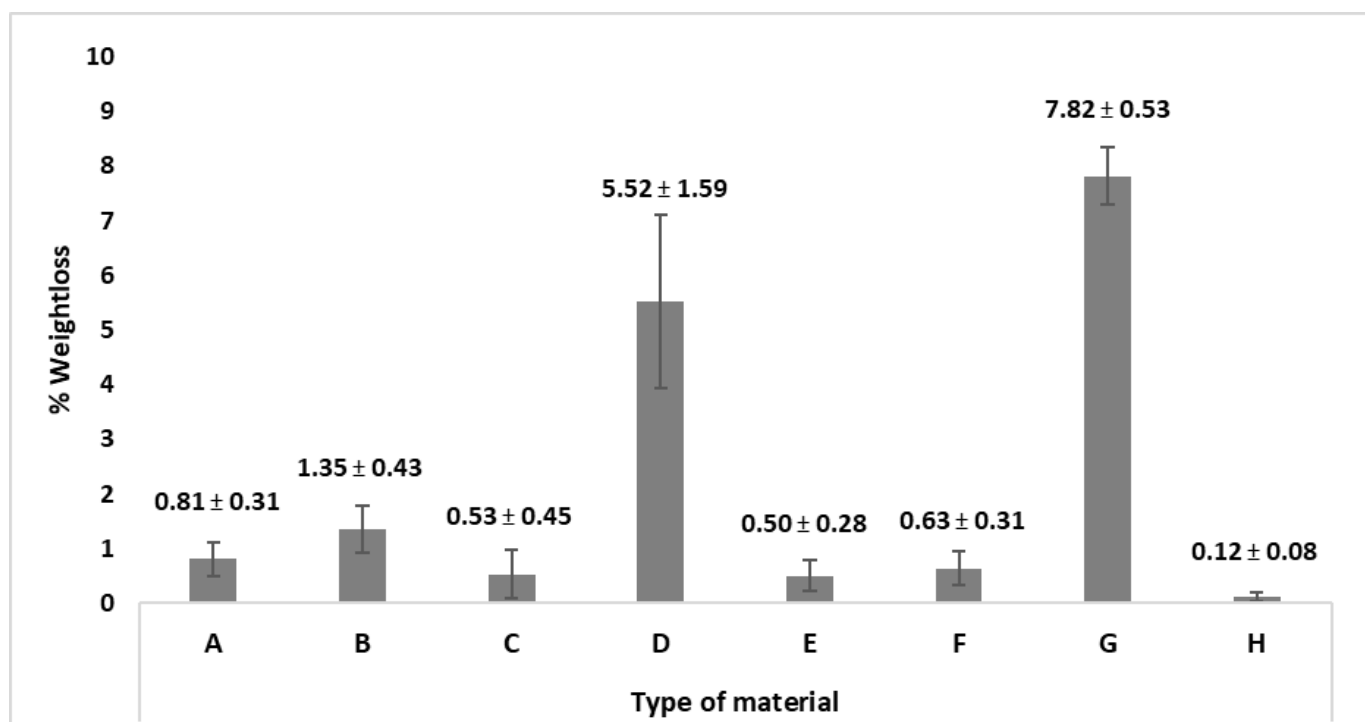


Figure 2. Weight loss of the material samples after being subjected to the action of five types of xylophagous fungi. A = 10% banana fiber-reinforced composite materials, B = 15% banana fiber-reinforced composite materials, C = 10% goose feather fiber-reinforced composite materials, D = 15% goose feather fiber-reinforced composite materials, E = 10% fique fiber-reinforced composite materials, F = 15% fique fiber-reinforced composite materials, G = pine wood, and H = recycled plastic, along with their standard deviations.

Table 3. Average weight loss of each of the evaluated materials, along with their standard deviation.

Materials	Starting Weight (gr)	Final Weight (gr)	Weightloss (gr)	% Weightloss
A	2.87 ± 0.084	2.8 ± 0.081	0.02 ± 0.015	0.82 ± 0.53
B	1.97 ± 0.085	1.94 ± 0.088	0.03 ± 0.014	1.37 ± 0.73
C	2.71 ± 0.107	2.69 ± 0.109	0.01 ± 0.014	0.55 ± 0.53
D	2.33 ± 0.114	2.2 ± 0.164	0.13 ± 0.062	5.51 ± 2.8
E	2.57 ± 0.198	2.56 ± 0.198	0.01 ± 0.008	0.52 ± 0.33
F	2.63 ± 0.127	2.61 ± 0.128	0.02 ± 0.009	0.66 ± 0.36
G	0.96 ± 0.060	0.89 ± 0.052	0.08 ± 0.011	7.81 ± 0.83
H	1.9 ± 0.37	1.9 ± 0.37	0 ± 0.004	0.13 ± 0.19

It is important to highlight that, although all the materials are highly resistant, according to the ASTM D 2017 standard, the material with 15% goose feathers and pine wood registered weight loss percentages well above the other materials, which did not exceed 2% in weight loss.

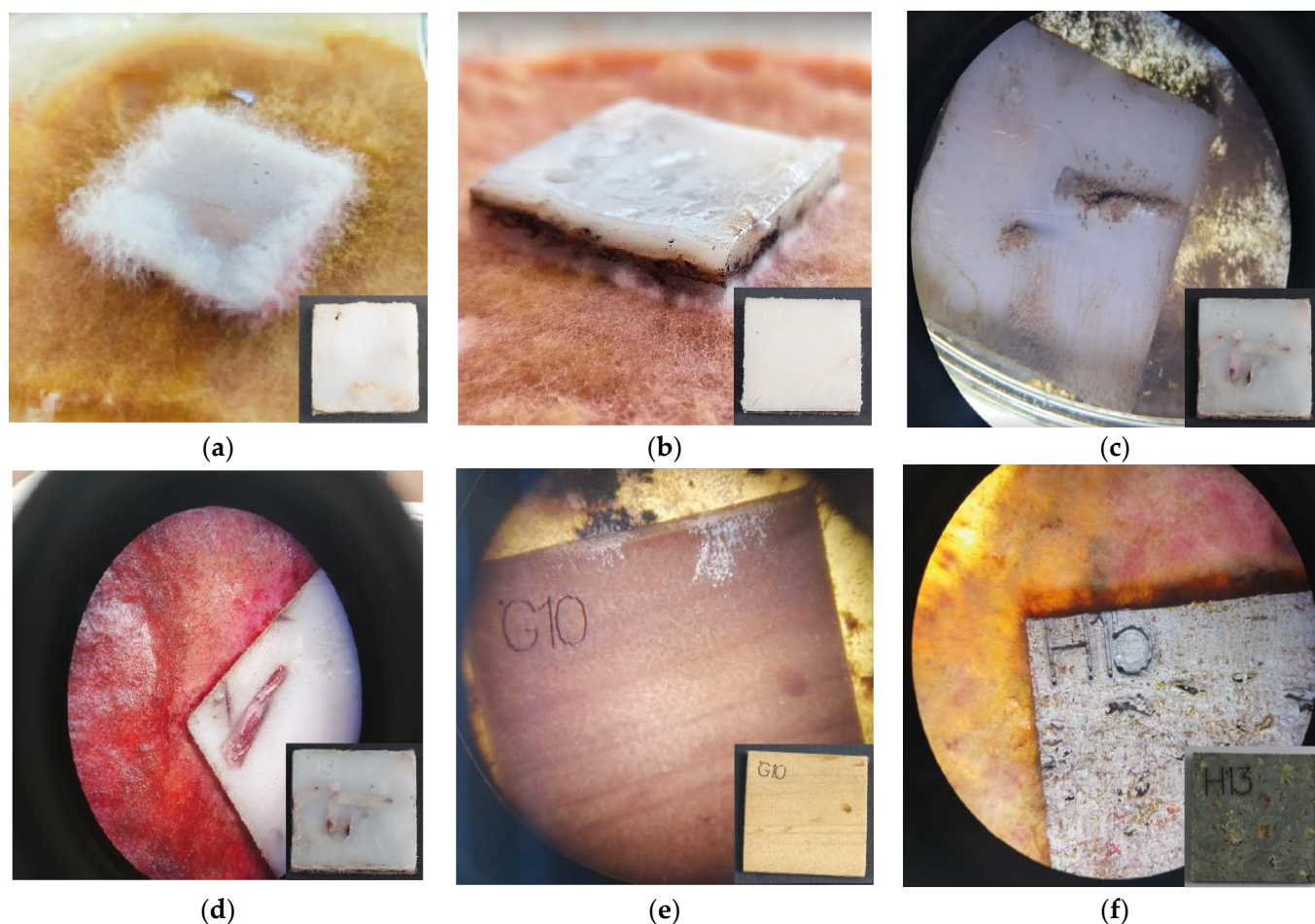


Figure 3. Xylophagous fungi growth in the different composite materials: (a) 10% fique fiber-reinforced HDPE; (b) 10% plantain fiber-reinforced HDPE, (c) 15% goose feather fiber-reinforced HDPE, (d) 10% goose feather fiber-reinforced HDPE, (e) pine wood (control material), and (f) recycled plastic.

4. Discussion

An analysis of the results displayed in the previous figures and tables demonstrated that, as expected, the wood samples present the highest percentage of weight loss, evidencing up to an 8% loss. These results are most likely due to it being a completely organic material, thus presenting a lower biological resistance to degradation. The 15% goose feather-reinforced composite samples also demonstrate a high percentage of weight loss, especially when compared to the 10% goose feather fiber-reinforced composite material. Indeed, the 15% goose feather reinforced composite material demonstrated a weight loss of up to 7%. This was the highest of any of the composite materials developed with recycled high-density polyethylene.

The recycled plastic samples exhibited the least weight loss, while the rest of the samples evidenced a weight loss of no more than 1%. This indicates that recycled plastic, as expected due to it being an inorganic material, demonstrates a very high resistance to rot. The fungi do not tend to attack it, as it lacks biological material in its structure. However, its production is dependent upon the use of polymers in the manufacturing process.

The data shown in the tables above demonstrate that the fungi that had the greatest effect on the materials were Fungus 3 and Fungus 4. All 5 fungi samples had a significant effect on the wood samples. Nevertheless, a variance analysis of the results showed that the percentage values of weight loss for the eight material samples revealed significant differences. This indicates that these materials are different in their behavior and resistance

towards the action of the xylophagous fungi used in this research. The differences in the interactions between the xylophagous fungi and the materials studied are significant, indicating that they influenced the results obtained for each species of natural material. The activity of the fungi in the experiment presented similar differences, generating weight losses of the materials in the test tubes and demonstrating an aggressiveness towards the organic portion of the samples. This caused decomposition processes to occur and affected the structural integrity of the hives. However, there are significant differences in the weight loss results of the tested materials when comparing the deterioration caused by the five types of xylophagous fungi.

As there were significant differences evidenced in the weight loss results for each of the evaluated materials, the results obtained from the xylophagous fungi causing the highest consumption of organic material were considered for classification due to their natural durability. Comparing the results to the ASTM D 2017 standard interpretation table, the eight samples were classified into category A: Highly Resistant. The wide range of the categories means that even though the species and materials presented significant differences in their weight loss results, all materials were classified in the same category. However, it should be noted that due to a great difference in the percentage of weight loss, two materials were approaching a categorization of B: Resistant. The results must be interpreted with the understanding that a high resistance to degradation is expected in materials with a higher amount of inorganic material than those with a higher content of organic reinforcement.

We recommend that future research should build upon these results to continue to contribute to the literature regarding beehive construction. The next step may be to use the best material that was identified in the present research in order to build a hive and place it in a real-life environment. This will allow for its structural degradation to be monitored, along with the fungal proliferation process, as well as for the determination of how it interacts with bees, food, and the environment.

5. Policy Implications

The regulation ASTM D2017-05 regarding the “standard method test for the accelerated natural degradation of woods” was eliminated by the authorities in 2014 in order to update the information and the resistance categories. Therefore, the present results might be useful in the determination of new resistance categories and the updating of the accelerated biological degradation procedures, in accordance with the present research regarding the degradation procedure using fungi collected from beehives from the case studies. It should be noted that all the materials evaluated in this study can be used not only for the construction of beehives, but for use in other construction fields as well.

6. Conclusions

According to the ASTM D 2017 standard for natural durability tests of wood and its interpretation table, all eight materials that were evaluated in this research were categorized as A: Highly Resistant. However, two types of material were close to being evaluated as B: Resistant, due to their weight loss percentages approaching 10%, indicating a lower durability.

We have shown that the composite materials developed from high-density polyethylene reinforced with 10% and 15% banana fiber, high-density polyethylene reinforced with 10% goose feather fiber, and high-density polyethylene reinforced with 10% and 15% fique fiber are the materials most recommended for the manufacture of beehives. This recommendation was arrived at due to the degradation parameter, since they are composite materials that are clean, use an organic residue, and exhibit a greater resistance to decomposition and fungal damage. Indeed, their average weight loss in the present study was just 1%, demonstrating a strong resistance to degradation compared to an 8% weight loss in the results for wood.

While recycled plastic may appear to be a great option, due to its low degradation rate and high resistance to fungi—attributed to its lack of organic components and biological affinity—its use in beehive construction can affect the purity of the honey. This is because of the source of origin of the polymers, which have a first manufacturing treatment of conformation and a second treatment of cleaning and reuse. In addition, the type of polymer with which recycled plastic is manufactured is not suitable for use in the food industry, as it is not approved for contact with food. However, high-density polyethylene is suitable for contact with food and is currently used in the food industry.

The xylophagous fungi used in the present study demonstrated a similar behavior within all the materials studied. This highlighted the resistance properties of the materials against the degradation caused by fungal proliferation. Over time, the fungi covered the surface of the materials evaluated. However, they did not affect every material in the same way, since the composition of cellulose and lignin found in the organic material determine where the fungi feed and proliferate, thus deteriorating the structure of the material. For this reason, wood was the material that evidenced the highest percentage of weight loss when compared to the rest of the materials. This is also evidenced by the normal deterioration suffered by hives in the beekeeping process, which leads beekeepers to the need for a total hive replacement every 4 to 5 years.

Due to the nature of the destructive test that the samples underwent in order to determine the effect of the fungi on the materials, it was not possible to observe the progress of the deterioration of each of the samples over time. Thus, we propose that future research should be conducted in order to evaluate the trend (linear or exponential) of the curve of the degradation effect. This could be achieved on a month-by-month basis for a minimum period of one year in order to monitor and document the fungal behavior and its effect on the durability of the material, allowing for a calculation of the projection of the useful life span of each material. This future research would have a direct impact on determining the useful life of the material under the real-world conditions in which fungi proliferate. It is also important to note that the biodegradation test was performed using biodiverse fungi collected from the case studies located in Boyaca, therefore, the authors of the present study strongly recommend that further research replicating this methodology be conducted with locally collected fungi, according to the location under study, due to geographical changes in biodiversity.

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