Soil Degradation of Sustainable PCB Substrates in Natural and Controlled Environments

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Abstract—**This paper compares natural and controlled soil composting, in which the degradation of flax-fiber reinforced, flame-retarded polylactic acid (PLA) composite printed circuit board (PCB) samples are monitored. We aim to investigate the structural alterations that occur over a prolonged degradation process of these biodegradable laminates, utilized as environmentally friendly substitutes for PCB substrates. The experiment involves the degradation of functional blinker circuits with surface-mounted components and blank substrate boards without a conductive copper layer. During the long-term storage, we registered the composition of the surface with Fourier-transform infrared spectroscopy (FTIR) and inspected the changes in structure with scanning electron microscopy (SEM). Compared to traditional epoxy-based (FR4) references, significant changes (at both microscopic and visible levels) and the susceptibility to natural organisms can be observed, key elements in developing a greener and more sustainable approach for future PCB designs. After 40 weeks, the FTIR analysis showed the dominant presence of PLA in the naturally degraded samples. Cellulose, which acts as component of the reinforcement, could be seen at specific locations within the cracks. The SEM study revealed contaminations and microbiological remnants on the boards' surface, along with a growing number of cracks and slight PLA deterioration. The FTIR and SEM results also highlighted the efficiency of the controlled degradation, as a significant loss of resin in the composite started after 6 weeks.**

Keywords—green electronics, sustainable PCB, FTIR, SEM, soil degradation

I. Introduction

One of the most urgent environmental issues is the accumulation of e-waste, which must be addressed as the electronics sector moves toward more sustainable operations. With recycling rates lagging far behind the rising e-waste accumulation, it is crucial to address the urgent challenge of hazardous waste management [1]. Besides recycling and end-of-life management, developing and applying eco-friendly materials are essential to innovative design and novel manufacturing methods. These approaches support the pursuit of sustainable industrialization (SDG 9) and sustainable communities (SDG 11) among the United Nations' Sustainable Development Goals.

Implementing and testing various alternatives is essential for advancing the sustainability of electronic devices, as traditional glass-reinforced epoxy substrates significantly contribute to the accumulation of unmanageable environmental waste. Because of its enormous potential as a reliable and green substitute for traditional PCB substrates, Polylactic acid (PLA) is often used for prototype development [2-9]. PLA is a bio-based polymer characterized by its biocompatibility, biodegradability, relatively good mechanical strength, nontoxicity, non-irritation, and processability. It can be synthesized through low-energy processes, and it does not depend on petroleum resources [10]. While these attributes make PLA a promising foundation for green electronics, thermal stability and electrical properties require enhancement for broader acceptance [11]. To address this issue, incorporating protein fibers like wool can significantly improve the thermal stability and flame resistance of the PLA matrix [12]. Additionally, maintaining usability requires careful temperature management during assembly and soldering, such as limiting the maximum temperatures of soldering profiles with special solder alloys or reducing the fabrication stages that involve elevated temperature settings [4, 13, 14].

The analysis of processing strategies for disposed electronics is a significant issue, making the study of the degradation of innovative materials essential. These examinations play a vital role in enhancing the composition and performance of biopolymers, ultimately contributing to more sustainable solutions for electronic waste management. For this reason, soil degradation is a suitable method, where samples (PLA and other biodegradable materials) are placed in composting bins [15-17]. However, PLA can only degrade totally in a controlled environment (using industrial or laboratory equipment and following a standard procedure); the decomposition process can also be initiated in natural outdoor circumstances. In the latter case, only partial decomposition can be achieved, and a longer composting time is also required. To realize the highest level of sustainability, the total biodegradability of mass-produced electronics requires more research since environmentally friendly inks and electrical components must be developed [18].

This research is part of an iterative development process in which the composition of a novel flame-retarded PLA-based substrate material with flax-textile reinforcement is continuously refined based on various testing results. To address environmental factors and decomposition behavior, we aim to investigate the structural variations in flax-fiber-reinforced PLA boards over an extended composting period and to compare the results of natural decomposition with those observed under controlled conditions.

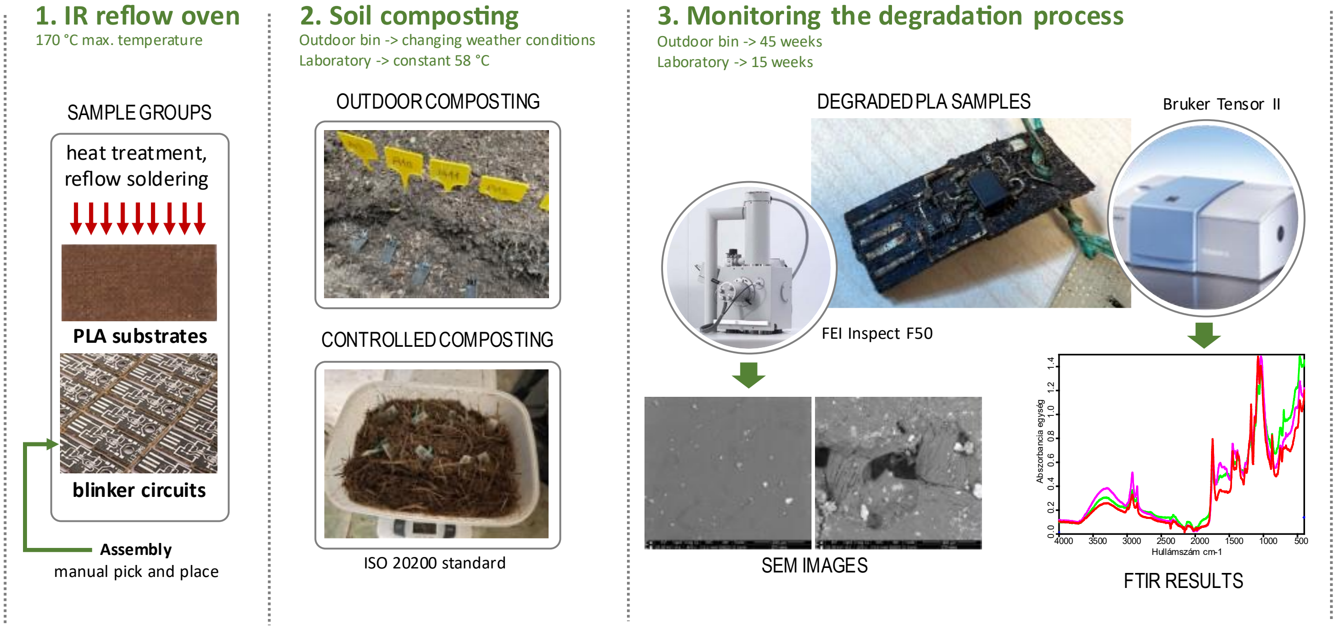

Fig. 1. Process of natural and controlled soil decomposition

II. Experimental

A. *Sample preparation*

Figure 1 shows the stages of the long-term decomposition procedure. In the case of the outdoor composting process, 16 copper-stripped substrates (40x20mm) and 16 assembled blinker circuits (10x35mm) were prepared. For the functional circuit boards, surface-mounted components were installed, and reflow soldering was performed (BiSnAg alloy, with a maximum profile temperature of 170 °C) after a subtractive method created conductive traces on the board's surface, and traditiona one-sided assembly was performed with stencil printing and manual pick and place. The bare laminates were exposed to the same heating profile as the assembled panels; all thermal treatments were performed in a Eurocircuit eC-Reflow-Mate oven, which operates with infrared heating. Our previous papers detailed the production of laminated PLA/Flax boards and the monitored weather conditions of the natural composting process [4, 19]. The controlled decomposition included 12 blinking circuits from the same manufacturing series; the samples were divided between two bins. For reference, both sample groups included traditional epoxy-glass (FR4) boards. The top side of the circuits involved an experimental bonding layer (polypropylene) under the copper, however the bottom sides had exposed PLA.

B. *Soil degradation processes (composting)*

The controlled soil degradation was conducted according to the ISO 20200 standard. The medium comprises sawdust (40%), rabbit feed (30%), ripe compost (10%), corn starch (10%), saccharose (5%), corn seed oil (4%), and urea (1%). After preparing and mixing the components, the samples were placed in the compost. The bins were set in a laboratory oven at 58 °C-62 °C to initiate the thermophilic incubation period. The standard process contains regular mixing and water resupply (restoring the reactor to the initial weight value), while different samples are continuously taken out for SEM and FTIR examinations. These panels are not put back in the bin, as they are prepared for further destructive investigations – these ongoing measurements will be evaluated later. Before the decomposition analysis, samples were brushed and dried for 24 hours, and the assembled sides of the boards were removed, with the samples carefully separated along the laminated layers. The boards from the outdoor bin were removed for SEM and FTIR analysis during the 30th, 40th, and 45th weeks of degradation. After examinations were performed, the selected samples were returned to the soil bin. The details of the time and samples for this procedure are reported in Table 1, while Table 2 outlines the schedule for the controlled degradation process.

TABLE I. SCHEDULE FOR SEM AND FTIR EXAMINATIONS DURING THE NATURAL COMPOSTING PROCESS

Date	**Sample**	**Examination**
2024 May (45th week)	deg_PCB05	SEM
2024 April (40th week) 2024 May (45th week)	deg_PCB15	SEM, FTIR
2024 February (30th week) 2024 April (40th week) 2024 May (45th week)	deg_PCB16	SEM, FTIR
2024 February (30th week) 2024 April (40th week) 2024 May (45th week)	deg_SUB16	FTIR
2024 May (45th week)	FR4(REF)	SEM

TABLE II. SCHEDULE FOR SEM AND FTIR EXAMINATIONS DURING THE THERMOPHILIC INCUBATION/CONTROLLED DEGRADATION (ISO 20200)

Day	Date	Removed PCB samples	SEM & FTIR examination
23	2024.07.31 (4th week)	1, 11	
51	2024.08.28 (8th week)	3, 12	1,11
58	2024.09.04 (9th week)	4, 13	
66	2024.09.12 (10th week)	5, 14	
81	2024.09.27 (12th week)	6, 15	3,4,5,12, 13, 14
94	2024.10.10 (14th week)	7, 17	
108	2024.10.24 (16th week)		5, 7, 15, 17
120	2024.11.05 (18th week)	2,8,9,10,16,18	
134	2024.11.19 (20th week)		2,8,9,10,16,18

C. *Monitoring the degradation process*

After cleaning and drying, the samples are prepared for visual inspection and optical microscopy. In this evaluation, we focused on the naturally degraded PCB boards and aimed to spot both mycelial presence and microorganisms, whether in residual or still active form. To evaluate natural and controlled degradation, SEM and FTIR investigations were conducted in the Failure Analysis Laboratory of the Department of Electronics Technology at BME. The SEM analysis utilized an FEI Inspect F50 device, while the FTIR inspection was performed with a Bruker Tensor II instrument.

III. Results

Figure 2 shows several PCBs from the outdoor decomposition process (sample IDs indicated in Table 1); these pieces represent the degrading status of the 45th week and are investigated from the bottom side of the PCB, where PLA is exposed directly to the environment. The reflective surfaces observed indicate the presence of PLA, while the uneven shine suggests that the thicker sections of the PLA have fragmented in certain areas. This fragmentation may impact the overall integrity and appearance of the material. For an accurate visual comparison, the label “deg_PCB” represents a “fresh” substrate that has avoided soil burial in this figure.

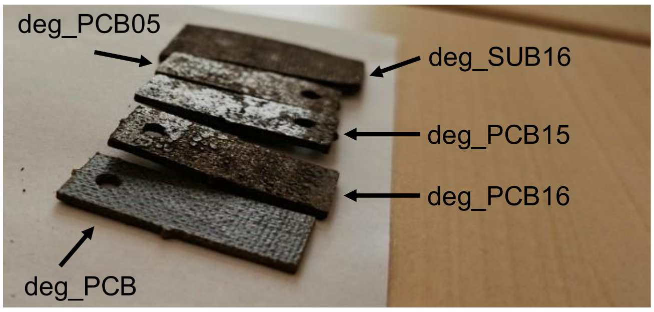

Fig. 2. PLA samples from the outdoor composting bin after 45 weeks of degradation (deg_PCB – reference PLA board that was not composted)

Figure 3 presents optical microscope and SEM images of the upper side of the PCB05 sample, where an additional polypropylene (PP) adhesive film surface (between copper and PLA) shows chipping, and the conductive strips display significant oxidation. It must be noted that the PP layer is not present on the non-conductive (bottom) side of the PCB design in this lot. It is applied over the PLA/Flax core to improve Cu adhesion to the surface as a minor compromise over total degradability.

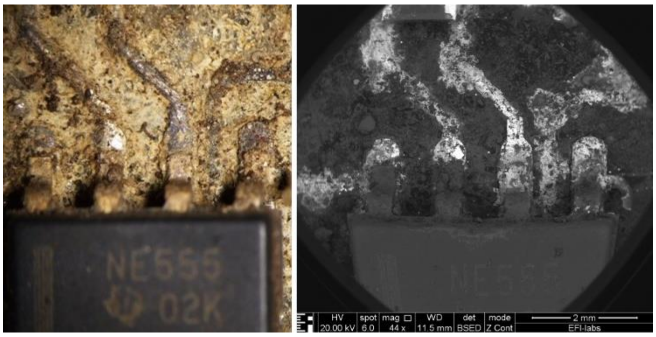

Fig. 3. Surface of PLA board (top side – deg_PCB05) after 45 weeks of degradation in the outdoor composting bin

Figure 4. shows visible PLA fragments on the bottom sides, which are the material piles that emerge during soldering due to the heating. Additionally, signs of mechanical fragmentation can be observed. The topological formations, which resemble bubbles, likely indicate two key phenomena: the heat-induced exudation of the resin surrounding the skeletal structure and the locations where mechanical fragmentation has occurred.

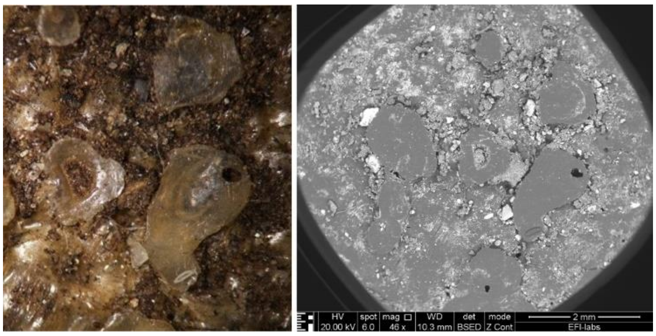

Fig. 4. PLA fragments on the surface of a composted board (deg_PCB16) after 45 weeks of outdoor degradation

In Figure 5, mycelial structures (hyphae) are visible on outdoor degradation on the bottom sides of the PCBs after ~40 weeks of degradation. This structure was visible during springtime, meaning that lifeforms appeared on the back sides of the samples with warmer periods (continental weather, Budapest, 2024 spring). This investigation needs further validation on the microbiological level, which was not possible during the writing time of the article. Microorganisms were completely missing from control FR4 samples.

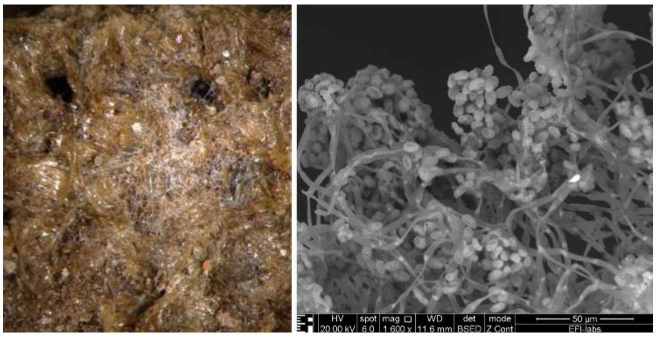

Fig. 5. Mycelial presence (hyphae) in PLA substrate (deg_SUB16)

It has to be summarized that degradation was not obvious in many aspects of the naturally set environments. First of all, the contaminations from the living organisms show promising susceptibility to the processes in the soil, however, it is not straightforward to identify the various lifeforms appearing on the samples. Also, it is challenging to continue measurements with already investigated samples, as SEM clears the surfaces from continuous development. The chipping of surfaces is apparent from the SEM images and qualitative optical observations. (See Fig. 2.) Later, the FTIR results will be presented in more detail, and further thoughts can be found in [20].

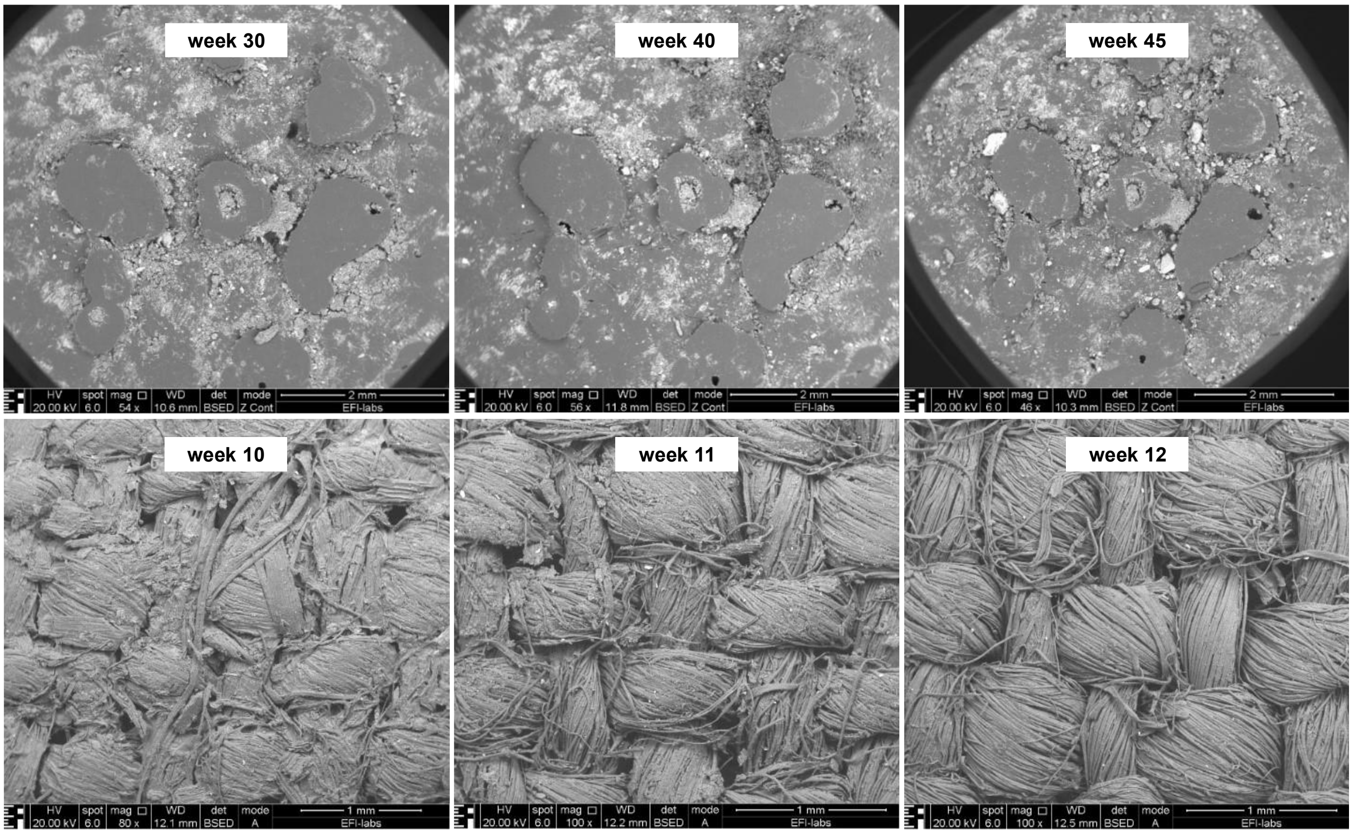

Fig. 6. Comparison of decomposed PLA surfaces in case of natural (top) degradation (~30-45 weeks) and controlled (bottom) soil degradation (10-12 week)

Figure 6 compares natural (top) and controlled (bottom) soil degradation. It is apparent from the already presented PLA islands (Fig 4.) that the samples are difficult to clean, and degradation is only marginal – only surface cracks and chips are visible in specific locations. On the contrary, the controlled degradation shows clear removal of the resin from the surface of the samples. Week 10 shows extensive coverage, with fewer loose filaments on the reinforcement material. And while weeks 11-12 still show resin in between the filaments, the structure of the material is loosened, which shows the release of the textile reinforcement from the resin. Figure 1 shows a comparison between week 20 and week 45, further emphasizing the reveal of the reinforcement from a practically smooth resin-covered surface.

Figure 7 presents the FTIR spectrum (absorbance values) of two samples obtained from the 45th week. While the top side of the sample is still dominated by the peaks of the PLA, the bottom side is starting to lose the database information related to the PLA. The remaining characteristic can be attributed to the database information related to cellulose.

Figure 8 presents a larger scale comparison between the spectrum of the PLA, the spectrum of samples measured after 14-15 weeks of controlled degradation, and the spectrum of cellulose. While the cellulose and PLA spectrums are interesting on their own (and can be related to the data shown in Figure 7, too), the central spectrum plots show the loss of the PLA and the appearance of characteristic cellulose on the surface. There are other components also measurable on the samples, which require further analysis. However, it is clear from the results that in a much shorter time (~10-15 weeks compared to 40-45 weeks), the PLA degradation is observed visually and characteristically with FTIR's help.

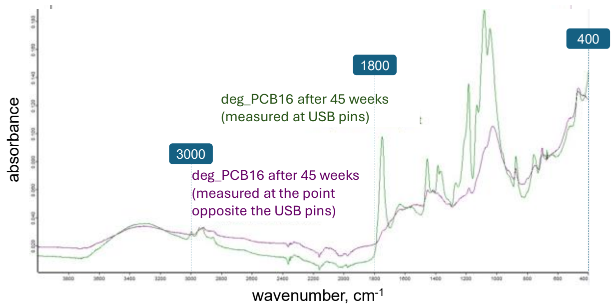

Fig. 7. FTIR spectrum of a naturally composted PLA sample

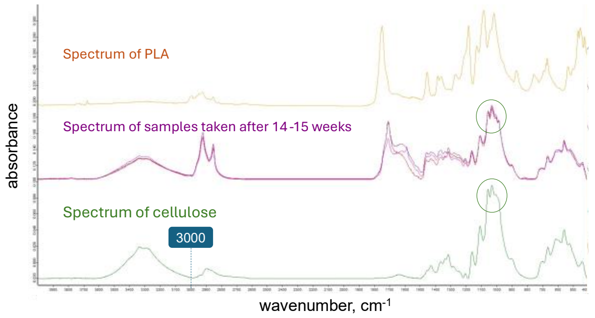

Fig. 8. FTIR spectrum of a PLA sample from controlled decomposition

IV. Conclusion

The paper presents the natural and controlled soil degradation of PLA/Flax-substrate-based sustainable PCBs, where the base composite is degradable, albeit the degradability of the assembled PCBs required analysis on different scales. It was shown with SEM images that the degradability of the samples is difficult to follow optically on the naturally degraded samples; however, after 45 weeks, FTIR confirmed the loss of PLA over the flax textiles. Also, microorganisms appeared during the period of degradation, which confirms compatibility with biological systems. (No similar organisms were found with FR4-based samples.)

It also has to be noted that SEM directly revealed the loss of resin from the reinforcement layer along weeks 1-10-11-12, with loosened fibers on the reinforcement after the 10th week was reached. FTIR confirmed our results (cellulose was dominant, and PLA was practically removed from the surface). However, further analysis is needed to see the complete spectrum of the degraded samples.

Future investigations will involve biological analysis of the given samples. (Also, controlled degradation needs further analysis of the present degrading lifeforms.) Different generations of the substrate with different bonding layers (such as the PP presented on the circuits' top side of the boards) should be evaluated.

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