Express Polymer Letters Vol.19, No.6 (2025) 554–555
Available online at www.expresspolymlett.com
https://doi.org/10.3144/expresspolymlett.2025.41

Editorial corner – a personal view

Sustainability in the electronics industry: Recycling opportunities of printed circuit board waste

Dániel Gere[1*], *Tamás Bárány*[1,2*]

[1]Department of Polymer Engineering, Faculty of Mechanical Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3., H-1111 Budapest, Hungary
[2]MTA-BME Lendület Lightweight Polymer Composites Research Group, Műegyetem rkp. 3., H-1111 Budapest, Hungary

According to Plastics Europe, 390.7 million tons of plastic were produced, of which only 7% was used for electrical and electronics applications (https://plasticseurope.org/knowledge-hub/plastics-the-facts-2022/). The lifetime of electrical and electronic products is usually 8±2 years; however, recycling the resulting waste is often challenging and may not always be feasible (https://doi.org/10.1126/sciadv.1700782). An interesting fact is that the majority of waste from electrical and electronic equipment (WEEE) is generated not by industry but by public consumers in the form of small telecommunication devices such as tablets, telephones, notebooks, televisions, small equipment (*e.g.*, microwave oven, vacuum cleaner), and large household appliances (*e.g.*, washing machines and refrigerators) (https://doi.org/10.1016/j.susmat.2024.e00902).

A United Nations Environment Programme reported that the annual WEEE production is 50 million tons, of which only 20% is recycled on average. A significant part of WEEE consists of printed circuit boards (PCBs), which account for 4–7% of the total weight (https://doi.org/10.1007/s12541-024-01027-2). However, recycling PCBs is complex and expensive due to the diversity of components and materials. They contain metals, ceramics, glasses, organic resins, plastics, *etc*., and the components must be separated from the carrier substrate, making it difficult to recover the individual materials efficiently. The most commonly used rigid substrate for PCBs in the electronics industry today consists of epoxy resin reinforced with glass fibers and often includes flame retardants. (https://doi.org/10.1002/adsu.202400518). The metal parts of PCBs can be recovered using hydrometallurgical, mechanical or pyromechanical processes (https://doi.org/10.1016/j.susmat.2024.e00902). However, this editorial corner focuses on the recyclability of these rigid plastic substrates.

Most non-metallic components used in PCBs are often not reused or recycled but incinerated or landfilled, which can lead to significant environmental damage. Furthermore, the material produced is not reused, which does not help the goals of a circular economy (https://doi.org/10.3390/molecules28176199). Several options exist for recycling non-metallic PCB materials, including chemical (*e.g.*, pyrolysis and depolymerization) and mechanical recycling. However, research suggests that mechanical recycling is the simplest and most effective approach, as the metal-free ground PCB powder can be effectively used as a filler in construction products, asphalt, and polymer composites. Over the past few decades, several studies have investigated the applicability of PCB powder as filler in various polymer matrices, including thermoset resins (*e.g.*, epoxy and polyester resins), thermoplastics (*e.g.*, polyethylene (PE), polypropylene (PP), poly(vinyl chloride) (PVC), and acrylonitrile–butadiene–styrene (ABS)), and rubbers. Due to its wide availability and low cost, non-metallic PCB powder can be used to improve the mechanical

*Corresponding author, e-mail: gere.daniel@gpk.bme.hu (Dániel Gere)
barany.tamas@gpk.bme.hu (Tamás Bárány)

properties, thermal stability, and flame retardancy of polymer composites (https://doi.org/10.3390/molecules28176199). It can also replace conventional fillers such as silica and talc in thermoset composites, effectively enhancing mechanical strength and modulus (https://doi.org/10.1016/S1007-0214(07)70041-X).

Non-metallic PCB powder has also been shown to improve the tensile and flexural performance of composites with thermoplastic matrices (PP and PE) significantly (https://doi.org/10.1016/j.jhazmat.2008.07.008 and https://doi.org/10.1016/j.jclepro.2013.05.033). However, residual metal contaminants (*e.g*. Cu and Fe) in PCB powders can accelerate the degradation of PP molecular chains, limiting the applicability of PCB powder (https://doi.org/10.1002/app.48224). In the case of PVC matrix composites, the diameter and content of glass fibers recovered from PCBs significantly influence the tensile and flexural strength of the composites (https://doi.org/10.1016/j.jenvman.2010.07.014). In wood–plastic composites (WPC), PCB powder can partially replace the wood content while also improving mechanical properties (https://doi.org/10.1021/es902889b).

Research has also investigated the potential of PCB powder as a curing additive and reinforcing filler in a styrene-butadiene rubber (SBR) matrix. Adding 5 phr PCB powder could accelerate the crosslinking process. In addition, inorganic metal derivatives in the PCBs (*e.g*., ZnO, MgO) may enhance curing efficiency (https://doi.org/10.1002/pc.25533).

There is significant research into replacing the traditional glass fiber–reinforced thermoset polymers used in PCB substrates with bio-based and biodegradable plastics. In these cases, biodegradable materials such as polylactic acid (PLA), cellulose acetate, poly(vinyl alcohol) (PVA), polyhydroxy butyrate (PHB), silk, gelatine, and mycelium could serve as a matrix. Bio-based and biodegradable reinforcements, such as banana fibers, wood, rice husk, kenaf, seashells, jute, and flax, can also be used. PCBs must comply with the UL standard 94 V-0 classification, which requires flame retardants to achieve the necessary level of flame resistance. Similarly to other applications, phosphorus and hydroxide-based compounds are used in the matrix to replace halogenated substances. After removing metal and non-plastic parts, biodegradable substrates can be decomposed in suitable environments (*e.g*., industrial or home composting), offering potential advantages over the recycling options of thermoset PCBs. However, if waste management is not proper and non-plastic contaminants remain on the laminate or are placed in an inappropriate environment, they may not decompose completely, and their environmental benefits may not be fully realized (https://doi.org/10.1007/s12541-024-01027-2 and https://doi.org/10.1002/adsu.202400518). Furthermore, the impact of additives used in the polymer matrix (such as flame retardants) on the biodegradability of PCBs and the quality of compost remains uncertain.