A Sustainable Writing Instrument Using Biodegradable PHA-Starch Polymers and Pollution-Derived Carbon Ink

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Abstract: This article explores a novel approach to sustainable writing instruments by combining two eco-innovations: a biodegradable pen body made from a PHA starch plastic blend and ink derived from carbon waste captured from pollution sources. Unlike prior efforts, where soot-based pigments required mixing with water for paint-like applications, this concept uses a safe, child-friendly polyol-based carrier system (propylene glycol, glycerin, PEG-400) to produce ink with the same texture and flow as everyday pen inks. The project highlights material selection, chemical safety, purification workflows, and the engineering of a refillable prototype. It bridges three perspectives: electrical and electronic systems thinking, material science, and sustainability impact.

Keywords: *Biodegradable Polymers, Carbon Waste–Derived Ink, PHA–Starch Polymer Blends, Sustainable Product Design, Circular Economy.*

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I. INTRODUCTION

The accelerating pace of global consumption has brought unprecedented convenience to modern life, but it has also intensified environmental challenges, particularly those associated with everyday disposable products. Among these, writing instruments pens, markers, and highlighters represent a deceptively small yet cumulatively significant source of plastic waste. Billions of pens are manufactured annually worldwide, the majority composed of petroleum-derived plastics and filled with inks that rely on synthetic dyes and solvents. These instruments are typically discarded after limited use, contributing to landfills, microplastic pollution, and long-term environmental degradation. Despite the digital transformation of communication, handwritten notes remain deeply embedded in education, design, engineering, governance, and personal expression. Consequently, the demand for pens persists, making them a compelling target for sustainable redesign. Addressing the environmental footprint of such ubiquitous objects requires innovation that extends beyond superficial material substitution and instead rethinks the entire product lifecycle from raw material sourcing and chemical safety to usability, refill ability, and end-of-life impact[1]-[2].

Sustainable product design has increasingly emphasized biodegradable polymers and recycled materials as alternatives to conventional plastics. In this context, polyhydroxyalkanoates (PHAs), a family of biopolymers produced by microbial fermentation, have emerged as promising candidates due to their biodegradability, biocompatibility, and renewable origins. However, PHAs alone often present challenges such as brittleness, cost, and processability, limiting their widespread adoption in consumer products. Blending PHAs with starch a widely available, inexpensive, and biodegradable polysaccharide offers a viable pathway to overcome these limitations while maintaining environmental benefits. Such blends can be engineered to achieve mechanical strength, flexibility, and moldability suitable for pen bodies, caps, and internal components. Yet, material substitution in the pen body addresses only part of the sustainability challenge. The ink itself, which is chemically complex and often overlooked, plays an equally critical role in determining the environmental and health impacts of writing instruments. Traditional inks frequently contain synthetic dyes, volatile organic compounds, and additives that raise concerns related to toxicity, indoor air quality, and environmental persistence[3]-[4].

Parallel to advances in biodegradable plastics, there has been growing interest in transforming waste streams into valuable resources, particularly in the context of carbon pollution. Carbonaceous waste such as soot and particulate

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matter generated from combustion processes has historically been viewed solely as an environmental hazard. Recent research and industrial initiatives, however, have demonstrated that these carbon-rich byproducts can be captured, purified, and repurposed as pigments, fillers, or functional materials. Early efforts in this domain largely focused on converting captured soot into pigments for paints, coatings, or inks intended for artistic and industrial applications. While these approaches represent an important step toward circular material use, they often rely on water-based or solvent-heavy formulations that result in paint-like textures rather than the smooth, low-viscosity flow characteristics expected of everyday pen inks. Moreover, such formulations may not meet the stringent safety requirements necessary for products intended for children, students, and widespread consumer use. As a result, the integration of pollution-derived carbon into common writing instruments has remained largely unexplored[5], [6].

This work addresses these gaps by proposing and exploring a novel combination of two eco-innovations: a biodegradable pen body fabricated from a PHA–starch plastic blend and an ink formulated from captured carbon waste using a safe, polyol-based carrier system. Unlike prior soot-based ink approaches that emphasized artistic applications, the present concept prioritizes functional equivalence with conventional pen inks in terms of texture, flow, drying time, and writing smoothness. The use of polyols such as propylene glycol, glycerin, and polyethylene glycol (PEG-400) enables the dispersion of purified carbon pigments in a stable, non-volatile, and child-friendly medium. These compounds are widely used in food, pharmaceutical, and cosmetic applications, underscoring their favorable safety profiles. The formulation strategy eliminates the need for aggressive solvents or hazardous additives while ensuring compatibility with standard pen refill mechanisms. In doing so, the project demonstrates how careful chemical selection and formulation engineering can reconcile performance requirements with health and environmental considerations[7], [8], [9].

Beyond materials and chemistry, this research adopts a systems-oriented perspective rooted in electrical and electronic engineering thinking. From this viewpoint, the pen is not merely a static object but a system comprising interconnected subsystems: material inputs, energy flows, manufacturing processes, user interaction, and end-of-life pathways. The refillable nature of the proposed pen design reflects principles commonly applied in electronic systems, such as modularity, maintainability, and lifecycle optimization. By enabling ink replacement without discarding the entire pen body, the design significantly reduces material throughput and waste generation. Additionally, the purification and processing workflow for pollution-derived carbon mirrors signal-conditioning and filtering concepts familiar in electrical engineering, where raw inputs are conditioned to remove noise and contaminants before being used in sensitive applications. This interdisciplinary framing highlights how engineering principles can be transferred across domains to support sustainable innovation[10], [11], [12].

Ultimately, this article aims to demonstrate that meaningful sustainability gains can be achieved not through isolated material substitutions, but through integrated design strategies that simultaneously address materials science, chemical safety, engineering functionality, and environmental impact. By combining a biodegradable polymer blend with a pollution-derived, polyol-based ink system in a refillable prototype, the work illustrates a practical pathway toward reducing the ecological footprint of a common yet impactful consumer product. The approach challenges the notion that sustainable alternatives must compromise on performance, safety, or user experience. Instead, it suggests that thoughtfully engineered eco-friendly writing instruments can meet or even exceed the expectations set by conventional products. In doing so, the project contributes to broader conversations on circular economy design, waste valorization, and the role of engineers and material scientists in shaping everyday objects that align with long-term sustainability goals.[13], [14], [15]

II. BACKGROUND

➢ *Pollution to Pigment*

Projects like KAALINK have proven that soot can be captured and processed into pigment for paints and markers. However, such inks often rely on water dispersions, making them more suited for art applications than precision writing. This work adapts the idea by replacing water with non-toxic, budget-friendly polyols that maintain suspension stability, flow, and smooth texture.

➢ *Bioplastics for Pen Bodies*

PHA (polyhydroxyalkanoates) are bio-based, biodegradable plastics suitable for injection molding. When blended with thermoplastic starch (TPS), they yield cost-effective, eco-friendly composites. PHA+TPS pens exist in concept, but pairing them with soot-based ink creates a unique integration.

➢ *Gaps Addressed*

- Safety: Ensuring inks are non-toxic and child-safe.
- Performance: Achieving smooth flow and everyday usability, not just paint-like texture.
- Sustainability: End-of-life biodegradability and measurable pollution offset.

III. METHODOLOGY

➢ *Pen Body Formulation*

- Composition: PHBV 65%, TPS 25%, compatibilizer 3%, mineral filler 5%, process aid 0.5%.
- Processing: Pre-dry pellets → twin-screw compounding at 160–175 °C → injection molding (160–180 °C melt, 25–35 °C mold temp).
- Design: Snap-fit body, refillable cartridge slot, uniform wall thickness for durability.

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➢ *Carbon Pigment Purification*

- Collect soot (safe pilot: candle soot).
- Dry sieve to remove coarse debris.
- Wash with isopropanol to eliminate oils.
- Treat with dilute HCl (0.1–0.5 M) to remove metals.
- Rinse with DI water until neutral.
- Dry at 70 °C.
- Ball mill or bead mill to sub-micron size (<200 nm ideal).

➢ *Polyol-Based Ink Formulation (Water-Free)*

- Propylene glycol: 50%
- Glycerin: 18%
- PEG-400: 16%
- Purified carbon pigment: 7%
- PVP K30 binder: 6%
- Polysorbate-80 dispersant: 0.7%
- Fumed silica: 0.6%
- Defoamer: 0.05%

- Properties: Viscosity 400–900 cP, stable dispersion, smooth rollerball flow.
- Advantage: No water → no microbial growth, longer shelf life, child-safe solvents.

➢ *Assembly*

- Fill refillable rollerball cartridges with filtered ink (0.45 µm).
- Insert into PHA+TPS body.
- Perform initial writing, smear, and cap-off tests.

IV. WORKING

➢ *Soot Collection System*

The first step is capturing pollution from the air. A small device called the pollution sucker uses a suction motor or mini vacuum pump to pull in polluted air. The air passes through multiple filter layers stainless-steel mesh, HEPA filters, and electrostatic plates which trap soot and carbon particles. The clean air is released back, while the collected soot gathers in a removable chamber.

➢ *Purification of Soot*

The soot collected often contains oil, dust, and metal residues. To purify it, the soot is washed with ethanol or isopropyl alcohol and distilled water. After filtration and drying, pure black carbon powder remains this becomes the main pigment for ink.

➢ *Conservation to Ink*

The purified carbon is mixed with safe, natural ingredients:

- Gum arabic – acts as a binder
- Glycerin – keeps the ink smooth and prevents it from drying quickly
- Distilled water and ethanol – for consistency and fluidity

This mixture is stirred until it becomes a rich, dark ink perfect for writing or drawing.

➢ *Filling the Ink Pen*

The prepared ink is filtered once more and then filled into refillable pen or marker bodies. The result: a smooth-writing Air Ink Pen a symbol of sustainability and innovation.

V. FEATURES AND BENEFITS

- Eco-friendly: Converts harmful air pollution into usable ink.
- Low-cost materials: Uses easily available filters, ethanol, and recycled pen bodies.
- Sustainable: Reduces soot emissions and promotes creative recycling.
- Educational impact: Raises awareness about environmental conservation.
- Scalable idea: Can be applied to industries, printing, and even art supplies.

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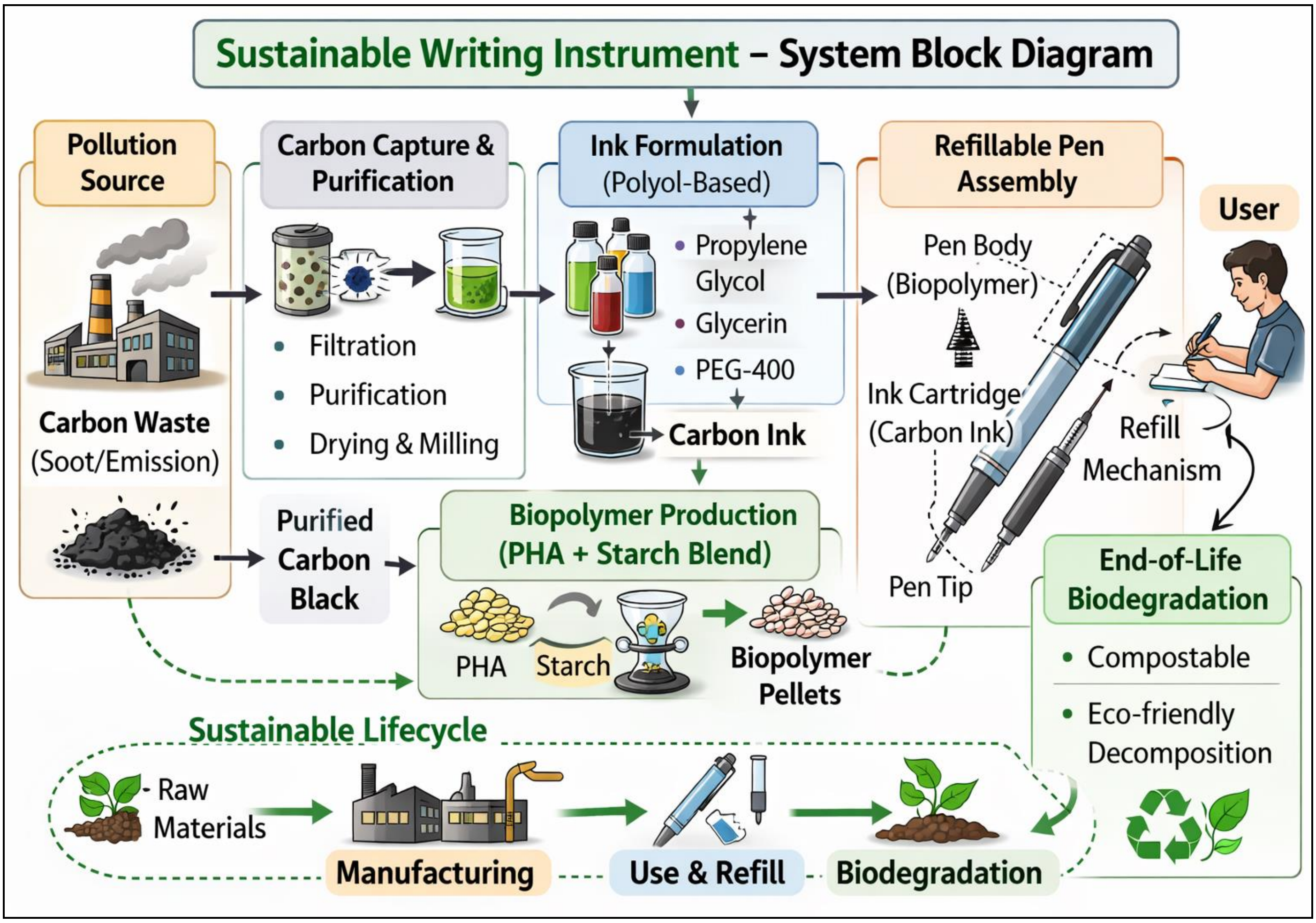

Fig 1 Proposed Work Architecture.

VI. CONCLUSION

This work demonstrates that sustainability in everyday consumer products can be significantly advanced through an integrated, system-level design approach rather than isolated material substitutions. By combining a biodegradable pen body fabricated from a PHA–starch polymer blend with an ink formulated from purified carbon waste using a safe, polyol-based carrier system, the study presents a practical and scalable pathway toward eco-friendly writing instruments. The proposed ink formulation successfully overcomes limitations of earlier soot-based approaches by achieving the viscosity, flow behavior, and writing performance comparable to conventional pen inks while maintaining chemical safety suitable for widespread and child-friendly use. Equally important, the refillable pen architecture extends product lifespan and reduces material throughput, aligning with circular economy principles and minimizing plastic and carbon waste generation. The interdisciplinary perspective adopted in this work bridging materials science, chemical formulation, and electrical and electronic systems thinking highlights how established engineering concepts such as modularity, conditioning, and lifecycle optimization can be effectively applied to sustainable product development. Beyond the technical contributions, the project underscores the potential of pollution-derived carbon as a valuable resource rather than a liability, reinforcing the broader notion of waste valorization. Overall, this study illustrates that environmentally responsible design can coexist with performance, safety, and user experience, offering a replicable model for reimagining other ubiquitous consumer products. Future efforts may focus on large-scale manufacturability, long-term biodegradation behavior, and quantitative life-cycle assessment to further validate and extend the impact of this approach.

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