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SUSTAINABLE

~95% of epoxy composites end up in landfills

73% of consumers willing to pay premium for sustainable

41% of bio-based materials come from bio waste

Composite toe cap of safety shoes impact to Environment

This document evaluates composite toe cap materials not on biodegradability-which is limited across all structural materials—but on carbon origin, process energy, recyclability, and regulatory resilience.

Europe's environmental policy targets climate **neutrality by 2035**, **emphasizing renewable energy, waste reduction, recycling, and sustainable material** use through strict regulations and national emissions-reduction commitments.

Conventional safety-toe caps are typically made from fiberglass reinforced with epoxy resin. Although mechanically effective, these **epoxy-based composites are non-recyclable, non-decomposable, and associated with high energy consumption and significant carbon dioxide emissions** throughout their life cycle.

To address these limitations, **Bio-Toe is introduced as a sustainable alternative**. Manufactured from a polyamide formulation **containing 41% bio-based nylon derived from non-food biomass**, Bio-Toe offers **lower life-cycle carbon emissions, mechanical recyclability, and the potential to achieve carbon-negative performance** under defined production and recycling conditions.

BIO TOE

Common epoxy-based composite used today include:

- **glass fiber**
- **carbon fiber**

Kessin innovative materials:

- **Bio-based polymer blends PA56**

Environmental Challenges of Epoxy-based Composites

Difficulties in Recycling and Circularity

Epoxy resins used in traditional fiberglass and carbon fiber composites form **irreversible thermoset structures** once cured. These *cross-linked* networks can not be melted or reshaped like thermoplastics. Most end-of-life epoxy composites are **landfilled or incinerated**, because conventional recycling methods fail to economically recover materials.

Mechanical recycling (e.g., grinding into filler) significantly **degrades mechanical properties**, meaning the recycled material often has *limited reuse value*.

Chemical recycling technologies exist in research but currently are **energy-intensive, costly, and not widely deployed** environmentally.

Production Footprint & VOC Emissions

Glass fiber production and epoxy manufacture are **energy-intensive processes** involving high heat and **petrochemical feedstocks**. The resin production in particular can emit **volatile organic compounds (VOCs)** and greenhouse gases.

This contributes to a **high combined environmental footprint** when assessed over the full life cycle — from material production through end-of-life.

Fiberglass composites are **not biodegradable** and can persist in landfills for decades or centuries. Separation of glass fiber from resin is technically possible, but expensive and energy-inefficient.

Environmental Attributes of Bio-Based PA56 Nylon

Bio-based PA56 incorporates carbon from renewable biomass sources in its feedstock. This means **part of the polymer's carbon footprint comes from sequestered atmospheric CO_2** rather than fossil fuels — reducing cradle-to-gate greenhouse gas emissions relative to fully petrochemical polymers.

Unlike thermoset epoxies, **thermoplastic polyamides like PA56** can be **remelted and reformed** at end of life, supporting *material circularity* rather than disposal or mechanically recycled into new products without degrading performance as severely as epoxy composites.

This thermoplastic behavior gives PA56 a **distinct environmental advantage** compared to epoxy resins, which lack any practical industrial recycling method today.

Research indicates that bio-based polyamide fibers (such as PA56) show **notable biodegradability** under certain conditions, whereas many petroleum-derived polymers persist much longer in the environment.

Table 1 — End-of-Life Recoverability of Epoxy-Based Composite Toe Caps
Comparison of epoxy matrix and fiber recovery routes, scalability, and industrial maturity

Method	Can It Recover Epoxy?	Can It Recover Fibers?	Scalable?	Remarks
Chemical	✗ (epoxy is degraded)	✔ (resizing needed)	! (expensive, toxic)	Used in labs/pilots
Thermal	✗ (epoxy burned)	! (fibers weakened)	✔ (industrial)	Used in cement kilns
Mechanical Grinding	✗ (epoxy lost)	✗ (fibers shredded)	✔	

Table 2 — Recycling Performance and Environmental Impact Comparison: Bio-Based PA56 vs Epoxy Composite Toe Caps
Material recovery yield, energy demand, cost, quality retention, and circularity potential

Criterion	41 % bio-PA56 / 59 % petro-PA cap	Epoxy-based thermoset composite cap
Form of waste	One polymer family	Cross-linked epoxy + glass/carbon mat
Primary recycling route	Re-grind → melt → injection mould new caps (closed-loop)	Only fibres recoverable
Typical recovery yield	80–90 % of polymer mass back into same-grade parts	50–60 % of fibre mass; 0 % of epoxy matrix
Energy demand per kg recovered	≈ 15 MJ (re-melt)	35–55 MJ (solvolysis / pyrolysis)
Quality loss after 1 cycle	< 10 % in Izod impact	20–30 % fibre strength; epoxy gone
Number of high-value loops	5–7× (industry data for PA)	1× (fibres need resizing)
Down-cycling option	PA → automotive clips, cable ties	Ground epoxy → filler for concrete / asphalt
Contamination sensitivity	Low – melt-filtration removes pigments	High – must separate resin, fibre, metal
Infrastructure needed	Standard PA recycling lines (exist worldwide)	Specialised thermoset plant (< 10 globally)
Cost of recovery	Around 0.3 € kg^{-1} (compounding + energy)	1.5–3 € kg^{-1} (chemicals + high heat)
Environmental credit (GWP)	Around –1.8 kg CO_2-e kg^{-1} vs virgin PA	Around –0.4 kg CO_2-e kg^{-1} (only fibres)

Table 3 — Functional and Sustainability Advantages of Bio-Based PA56 in Safety Toe Cap Applications

Implications for greenhouse-gas footprint, processing energy, worker safety, and regulatory compliance

Advantage of bio-PA56 toe-cap	Why it matters even if landfill life is the same
Around 40 % less fossil carbon in the pellet	Direct cut in greenhouse-gas footprint of the resin itself
Renewable feed-stock	Shields the brand from oil-price volatility and scope-3 reporting pressure
Injection-moulding cycle around 65 seconds vs 30 minutes epoxy cure	9× lower energy in the forming step; biggest contributor to the GWP gap
Re-melt-able (thermoplastic)	Mechanical recycling is possible; epoxy is irreversibly cross-linked
No styrene / amine VOCs during processing	Better indoor-air and worker-exposure scores
Meets upcoming bio-content mandates (EU, US federal)	Future-proofs the product against extended-producer-responsibility fees

Table 4— Indicative Primary Energy Demand for Toe Cap Materials (Cradle-to-Gate)

Values represent typical industry ranges for virgin material production; actual values depend on supplier, geography, and energy mix. Values are intended for comparative screening rather than precise product-level LCA.

Material Category	Typical Material Used in Toe Caps	Primary Energy Demand (MJ/kg)	Main Energy Drivers	Notes for Footwear Application
Glass Fiber	E-glass + epoxy	45–65 (glass fiber) + 70–90 (epoxy resin)	Fiber melting (~1500 °C), petrochemical resin synthesis	Epoxy matrix prevents closed-loop recycling
Carbon Fiber	PAN-based CF + epoxy	250–300 (carbon fiber) + 70–90 (epoxy resin)	PAN stabilization & carbonization	Highest embodied energy; limited reuse
Bio-Based	PA56 (41% bio-based)	60–80	Fermentation + polymerization	Lower fossil energy input; thermoplastic recyclability

Table 5— Recoverability comparison

Criterion	Epoxy Composite	Metals	Bio-PA56
Closed-loop recycling	No	Rare	Yes
Multi-cycle reuse	No	Limited	Yes (5–7×)
Infrastructure	Specialized	Heavy industry	Existing PA lines
Value retention	Low	Medium	High

Material Recoverability and Circularity Performance:

- **Bio-based PA56 toe caps**

  Bio-based PA56 material enables **mechanical recycling with high material retention**, typically recovering **>80% of polymer mass**, support **multi-loop recycling (5–7 cycles) with limited mechanical property degradation.**

  Recycling is **economically viable** (using standard polyamide recycling lines widely available globally) while retaining high material value. The recycled components can be reused in safety footwear or can be down-cycle into other industrial applications.

- **Epoxy-based composite toe caps**

  Only reinforcing fibers can be partially recovered, typically **once**, and with **significant strength loss**. The epoxy matrix itself is **not recoverable** and is destroyed during recycling.

  Recycling processes require **high energy input, specialized infrastructure, and chemical handling**, resulting in high cost and limited scalability.

  Overall circularity is low, with most material ultimately disposed of.

- **Health, safety, and regulatory considerations**

  The primary occupational risk of epoxy-based systems occurs during **manufacture and repair**, requiring strict PPE, ventilation, and exposure controls.

  Much epoxy-based toe cap production occurs outside the EU, where **regulatory enforcement and occupational standards vary**, yet products remain subject to EU market restrictions. Ongoing EU regulatory developments may further restrict certain epoxy chemistries, increasing long-term risk for epoxy-based footwear components.

Key Findings and Observations

- **Market and regulatory context**

  Approximately **73% of consumers are willing to pay a premium for sustainable materials**, indicating increasing market pull for lower-impact safety footwear solutions.

  The **EU regulatory roadmap (2026 onward)** continues to tighten restrictions on hazardous substances, including certain epoxy hardeners and CMR-classified chemicals, increasing long-term compliance risk for epoxy-based systems.

- **End-of-life limitations of epoxy-based composites**

  Around **95% of epoxy-based composite products are currently landfilled or incinerated** due to irreversible cross-linking of thermoset matrices.

  Advanced recycling methods exist at laboratory or pilot scale, but remain **energy-intensive, costly, and economically unviable** for the footwear industry. In practice, epoxy-based components (carbon fiber, glass fiber) recyclability has **minimal positive environmental impact** at industrial scale.

- **System-level complexity of epoxy-based toe caps**

  Epoxy resins are typically used in combination with **glass fiber or carbon fiber reinforcements**, creating multi-material structures. Even when “bio-epoxy” variants are used, the **composite structure itself prevents efficient separation and recovery**, making closed-loop recycling impractical for footwear applications.

- **Environmental advantage of bio-based PA56 toe caps**

  Bio-based PA56 toe caps derive **41% of polymer content from biomass waste feedstock**, reducing reliance on fossil carbon and unlike **epoxy composites, PA56 toe caps consist of a single thermoplastic polymer family, significantly reducing dismantling and recycling complexity.**

  Existing polyamide recycling infrastructure enables **practical closed-loop recycling** within footwear and adjacent industries.

- **Clarification on biodegradability**

  Bio-based PA56 is **not biodegradable under real-world disposal conditions**.

  The environmental advantage over epoxy composites is therefore **not related to landfill degradation**, but to **carbon origin, process energy, worker safety, recyclability, and regulatory resilience**.

Overall Assessment and Key Findings

When evaluated across carbon footprint, process energy, worker safety, regulatory resilience, mechanical performance, and end-of-life recoverability, bio-based PA56 toe caps offer the most favorable balance currently achievable among commercially available toe-cap materials, without compromising certified safety performance.

Bio-based PA56 toe caps optimize the protection-to-impact ratio by combining certified mechanical performance with reduced fossil carbon input, lower manufacturing energy demand, improved occupational safety during processing, and practical closed-loop recyclability—advantages that metals and epoxy-based composite systems do not deliver simultaneously.

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Berlin, Germany, 11 December 2025

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