BioPhenom: multifunctional biophenols for safe and recyclable materials

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The path to a zero-pollution future

Europe stands at a critical crossroads in its pursuit of climate neutrality, resource efficiency and pollution reduction. Current industrial systems are heavily dependent on fossil-based chemicals and materials, many of which pose risks to both human health and the environment. As part of the European Green Deal and the Circular Economy Action Plan, the European Commission (EC) has prioritised the development of safe, sustainable and circular solutions that can replace conventional resource-intensive products.

Within this context, the Horizon Europe project **BioPhenom** was launched to pioneer **safe-and-sustainable-by-design (SSbD) bio-based platform chemicals, additives and materials**. Funded under the call *HORIZON-CL6-2023-ZEROPOLLUTION-02*, the project is working at the interface of biomass and organic chemistry, materials science and sustainability assessment to create viable alternatives for multiple industrial applications. Its mission is not only to innovate at the molecular and process levels but also to set new benchmarks for environmental and human safety throughout the entire product life cycle.

The challenge: why we need bio-based and safe-and-sustainable-by-design alternatives

Fossil-derived chemicals and polymers remain deeply embedded in today's industrial economy, from packaging to textiles, automotive components and consumer goods. However, their production and use are often associated with greenhouse gas emissions, toxic substances and non-recyclable waste streams (European Environment Agency, 2020). While bio-based alternatives have emerged as a promising pathway, many of these are not intrinsically safe, nor are they always competitive in properties, performance or cost.

A major gap has been the **integration of safety and sustainability considerations from the very beginning of the design process**. Too often, chemical innovations are assessed only after development, leading to late discovery of potential hazards, regulatory challenges or lack of circularity. The EC has therefore strongly endorsed the **SSbD framework**, which calls for new chemicals and materials to be conceived with safety, environmental performance and socio-economic viability embedded upfront (European Commission, 2022).

From an industry perspective, the current implementation of SSbD can operate like a binary 'green/red-light' screen that over-weights intrinsic hazard; applied rigidly, these risks stalling otherwise beneficial innovation and should instead be embedded in stage-gated R&D with explicit treatment of trade-offs and exposure/use context rather than aiming for 'absolute safety'. Accordingly, SSbD should evolve toward a pragmatic, risk-based scheme that complements hazard with concentration-based thresholds, providing technology developers with actionable use-level guidance (Rajagopal *et al*., 2025; Cefic, 2024).

BioPhenom responds directly to this policy need by ensuring that every innovation produced under its umbrella is evaluated through rigorous sustainability and safety lenses from day one.

BioPhenom's main objective

BioPhenom will harness **biophenols from industrial biomass sidestreams** using advanced technologies such as fast pyrolysis and liquid extraction, transforming them into **bio-based intumescent flame retardants (bio-IFRs)**. Guided by SSbD principles to avoid regrettable substitutions, these **biophenols serve as feedstocks** for innovative applications across three material groups: PLA-based thermoplastic composites, bio-carbon fibre thermoset composites and wood products.

1. **Thermoplastic composites**: Polylactic acid (PLA)-based composites enhanced with biophenol-derived flame retardants and biochar. These will replace petrochemical-based plastics and harmful flame retardants, providing fire resistance, recyclability and reduced toxicity in applications such as insulation panels and floor coverings.
2. **Carbon fibre thermoset composites**: Biophenols will substitute acrylonitrile as the primary precursor in the production of carbon fibres, and bisphenol A (BPA) in the formulation of epoxy resins. Bio-based epoxy resin systems will be further developed by combining biophenol-based precursors with dynamic hardeners. The result: strong, lightweight composites for transport and aerospace applications that are safer, recyclable and high-performing.
3. **Impregnated wood products**: Wood for exterior applications, such as facades and terraces, will be treated with biophenol-based flame retardants that also improve biological durability. This dual-function alternative replaces boron compounds and toxic preservatives, ensuring recyclability and extended service life.

Methodological backbone: SSbD approach

BioPhenom applies the SSbD concept holistically, combining cutting-edge laboratory research with advanced modelling and life cycle analysis. The approach is structured around four pillars (Isigonis *et al*., 2025):

- **Early-stage hazard screening:** New molecules are computationally and experimentally assessed for toxicological and ecotoxicological properties at the design stage
- **Sustainability metrics:** Environmental, economic and social indicators are integrated to guide the selection of promising candidates.
- **Circularity and recyclability:** Materials are tested not only for performance but also for their potential to be reused, recycled or safely degraded at end of life.
- **Policy and regulatory alignment:** The project works closely with EU agencies and standardisation bodies to ensure that results are compatible with future regulatory frameworks.

This structured approach allows BioPhenom to reduce risks of costly late-stage redesigns while fostering innovation that can be trusted by regulators, industry and consumers alike.

Biomass sidestreams: unlocking hidden potential

One of BioPhenom's early achievements has been a comprehensive **scoping study of biomass sidestreams** from forestry, agriculture and food processing. These sidestreams—often treated as low-value fuels or even waste—hold enormous potential for high-value applications.

The study evaluated **ten sidestreams:** tree bark, sawdust, logging residues, cereal straw, fruit tree pruning residues, horticultural residues, grape stalks, olive stones, brewer's spent grain, and nut shells (Borrega *et al.*, 2025). They were assessed according to availability, biophenol content, logistics and current uses.

Key findings include:

- **Tree bark and grape stalks** contain the **highest concentrations of biophenols** (up to 40% of dry mass), making them prime candidates for sustainable extraction.
- **Tree bark and sawdust** are the most practical sidestreams, concentrated in industrial sites and **available year-round**, which simplifies collection and storage.
- **Cereal straw** is **Europe's most abundant sidestream** (>200 Mt/year), but low phenolic content and competing uses **(bedding, soil conditioner)** restrict its potential.
- **Olive stones and nut shells** provide **moderate phenolic content** and are underused beyond energy recovery, offering a balanced mix of availability and value.
- **Fruit tree prunings and horticultural residues** are **seasonal and geographically dispersed**, making large-scale exploitation difficult.

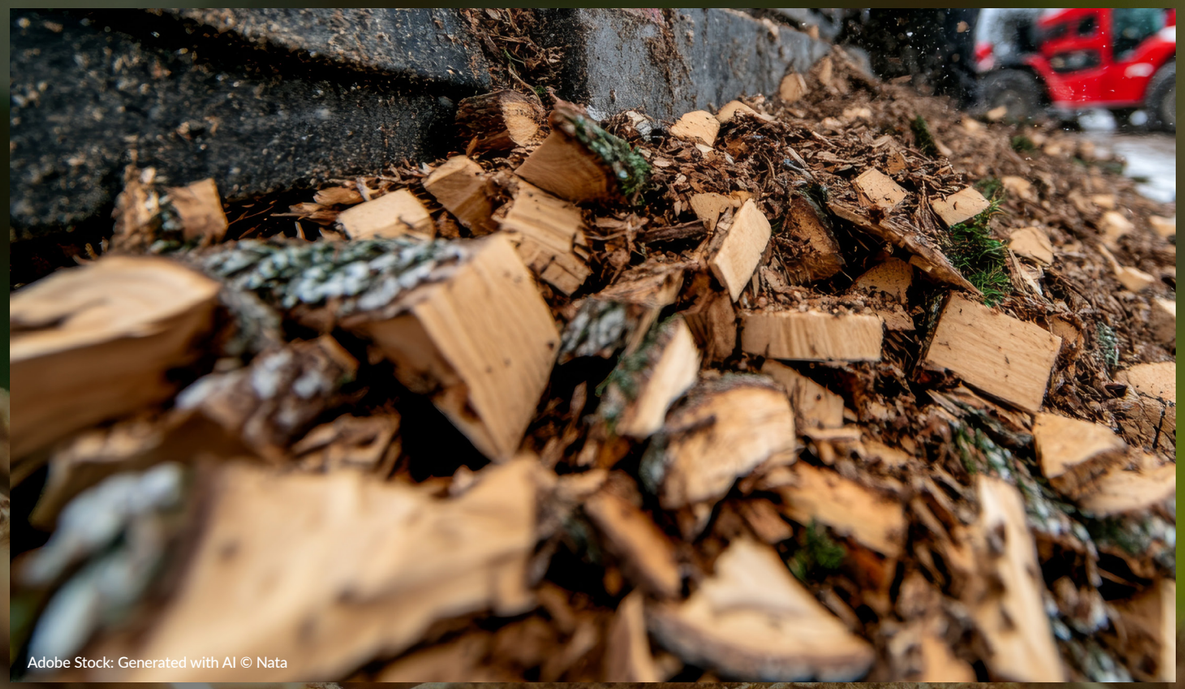
The ranked list places **tree bark, logging residues and grape stalks** as top candidates for exploitation. These resources will serve as the backbone for BioPhenom's material innovations.

Future outlook: BioPhenom's long-term impacts

BioPhenom is set to generate far-reaching impacts that resonate well beyond the project itself across several domains:

- **Scientific impact:** advancing the state of the art in bio-based chemistry and functionalisation of biophenols, while operationalising the SSbD framework with new data, models and methodologies. This contribution strengthens Europe's knowledge base in sustainable materials innovation.
- **Industrial impact:** demonstrating competitive, scalable and safe bio-based alternatives for sectors such as construction, automotive, aerospace, packaging and electronics. By reducing dependence on fossil feedstocks, BioPhenom reinforces Europe's leadership in sustainable chemicals and advanced materials.
- **Environmental impact:** replacing hazardous petrochemicals and substances of very high concern (SVHCs) with bio-based alternatives. The project will reduce greenhouse gas emissions, lower pollution and toxic releases, and enhance recyclability, directly supporting the EU's zero-pollution ambition.
- **Societal impact:** safeguarding human health through safer products, while creating opportunities for green jobs, new skills and consumer trust in bio-based solutions.
- **Policy impact:** providing robust evidence for European regulatory frameworks, including the Chemicals Strategy for Sustainability and the Circular Economy Action Plan, and showing how SSbD can be effectively applied in practice.

BioPhenom stands to reshape industrial value chains, easing environmental pressures while strengthening Europe's transition to sustainability. Its outcomes will not only advance safer materials and processes but also foster healthier societies and more resilient economies. The project thus emerges as a catalyst for a safer, circular and competitive European bioeconomy.



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PROJECT SUMMARY

BioPhenom develops safe, sustainable and recyclable materials by replacing harmful petrochemicals with biophenols extracted from industrial biomass sidestreams. Using fast pyrolysis and liquid extraction, the project creates bio-based flame retardants for wood, thermosets and thermoplastics. Guided by safe-and-sustainable-by-design principles, BioPhenom aims to support Europe's zero-pollution ambition and accelerate the transition to a circular bioeconomy.

PROJECT PARTNERS

BioPhenom unites 12 partners from ten European countries: five RTOs (VTT, NIBIO, LIST, CIDETEC, CNR), one university (University of Birmingham), and six SMEs (Nordtreat, INVENT, Specific Polymers, Edelweiss Connect, CRCF, TALOS). Together, they combine expertise in the fields of biomass and organic chemistry, materials science and technology, among many others, ensuring an integrated, multidisciplinary approach.

PROJECT LEAD PROFILE

VTT Technical Research Centre of Finland, one of Europe's leading applied research institutes, coordinates BioPhenom. With over 80 years of expertise in sustainable materials and biomass valorisation, VTT advances technologies from research to industrial uptake. In BioPhenom, VTT leads project management, biophenol isolation via pyrolysis and extraction, and their functionalisation into safe, bio-based flame retardants for circular applications.

PROJECT CONTACTS

Project Coordinator: **Dr Marc Borrega**, Principal Scientist, VTT

marc.borrega@vtt.fi

https://biophenomproject.eu

/showcase/biophenomeu

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