FINAL REPORT

# Advanced Biocomposites with Circular Design - ABiCo

ABiCo

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# Executive summary

Thermoplastic biocomposites containing thermally mouldable polymer and wood-based fibre or natural fibre as reinforcement are a class of materials used in construction since the 1960s. Polyolefin-based terrace planks and materials for external cladding containing sawdust or wood powder as reinforcement are still the main product category for biocomposites. Those are products with a relatively long lifetime. Challenges with durability against weathering are typically tackled using coextrusion and oil-based additives. Currently, there is a versatile selection of different biocomposites on the market containing oil-based, bio-based, and recycled polymers in combination with fibres from micro-size to long continuous fibres and side streams from different origins. The biocomposite market is estimated to double within the next five to ten years*. The selection of products is increasing, covering applications from consumer goods and packaging to furniture, covers for electronics, automotive parts, and novel uses in construction. Many of those applications require improved thermal resistance or even flame resistance grading, durability against special weather conditions and mould growth, and high mechanical performance. Current commercial bio-based polymers and natural or wood fibre-based materials are, however, suited to respond only to a part of the projected increased demand. Limitations include not being fully compatible with current industrial processing, not being able to fully meet target application requirements, and/or higher costs versus existing solutions.

The main drivers for biocomposite use are related to a regulatory push towards a more sustainable, low carbon footprint and low-weight materials. In the transition towards a more sustainable world, the use of virgin and non-renewable raw materials is becoming increasingly questionable. Scientific society is trying to find renewable-based or recycled solutions that meet specifications of currently used materials, are compatible with existing processing methods, and are recyclable, with lower environmental impacts such as carbon footprint and life-cycle cost (LCC). The key challenges of biocomposites are, in particular, related to recycling.

In the ABiCo project, we took a holistic approach by considering circular design as one of the project's main focuses. For raw materials, we selected potentially recyclable and/or recycled polymer materials from NG Nordic (former Fortum Waste Solutions), widely available wood-based fibres from Metsä Fibre and Pihla, and additives of renewable origin. As a result, we were able to create know-how related to materials, their processing, sustainability in window frame-related products and construction parts for ships, and recycling-related issues. In ABiCo project work at Åbo Akademi University (Åbo Akademi), flame-retardant properties were introduced into the composite materials providing a significantly improved limiting oxygen index (LOI) and, in some cases, they achieved a V-0 rating in the UL-94 test. To provide long-term stability and durability to the biocomposite materials, compositions using commercial thermal and UV stabilizers were developed. We demonstrated the potential of biochar and wood-based distillates prepared at the University of Eastern Finland (UEF) in bringing strength and long-term durability for biocomposites. Biochars and selected distillates studied at UEF also seemed to be safe to use as additives in biocomposites, based on VOC emission and cell testing.

We demonstrated in joint work with the Portuguese research organisation PIEP and VTT Technical Research Centre of Finland (VTT) how fibre containing biocomposites can be foamed during injection foaming for product weight reduction. At LAB University of Applied Sciences (LAB), we successfully 3D-printed an all bio-based material compound containing sawdust side-stream from the Pihla process. We also demonstrated how cellulose fibre can be modified with novel additives for improved performance using foam forming.

*e.g. Grand View Research, 2026 Global Market Insights, 2026 Fortune Business Insights, 2026

For biocomposite testing, an acoustic emission tool enabled us to identify cracking phenomena and failure modes as a novel test method developed at UEF. At VTT, we were able to prove applicability of hyperspectral imaging in identification of different fibre and polymer-containing biocomposites for more effective separation for recycling.

For more effective novel product design, a biocomposite material selection tool was developed at LUT University (LUT) as a dissertation required for a diploma. Design of potential products using biocomposites, and design proposals on component replacement in the context of material replacement towards sustainable manufacturing and reducing carbon footprint in the production phase, were studied at LUT in special student case studies. LCA analysis demonstrated up to a 40% reduction in environmental impacts through biocomposite material substitution in window components. The circular design strategies for windows also studied resource efficiency, lightweighting and modularity.

The ABiCo project was able to point out bottlenecks and challenges related to the recycling of biocomposites, which is highly related to recycling ecosystems for materials for specific products, volumes coming into recycling, scattered material streams, and logistics issues. The challenges are more society-related and should be solved together with recycling companies and municipal and governmental actors to get all materials recycled, including biocomposites.

Even though some challenges exist for biocomposites to enter the market with their full potential, the business development investigation showed that biocomposites fit the European Commission's bioeconomy strategy, which encourages further development of circular material solutions. At the same time, market demand for biocomposite-based products is increasing.

During two years of work, ABiCo was able to catalyse cross-disciplinary research between research partners in the form of 23 scientific publications so far, collaboration, and innovative discussions with industrial partners promoting the development of sustainable bio-based innovations. With the help of our industrial partners, we were able to reflect our aims and results in existing material environments, and with special thanks to NG Nordic and Syklo Biocomposites Oy. Global environment-related issues and coming EU regulations are pushing society towards the use of renewable and recycled materials with improved circularity, emphasising the need for recycling also for these novel materials and, most of all, product design for the circular economy.

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# ABiCo in a nutshell

Authors: Aila Maijanen, CLIC Innovation and Taina Kujanpää, CLIC Innovation

The Advanced Biocomposites with Circular Design (ABiCo) project aimed to demonstrate the potential of biocomposite materials in demanding applications, using circular design as a key methodology to advance sustainability and circularity. The objective was to enable biocomposites –natural fibre composites and especially wood-based thermoplastic polymer composites – to become a competitive material alternative in the markets currently dominated by virgin fossil-based plastics and glass fibre-based composites. By integrating circular and environmental design aspects into development, the project aimed to open entirely new application areas for biocomposites, as well as to support the emergence of innovative business models in industry. ABiCo was co-funded by Business Finland, the national innovation funding agency, through its Co-Innovation funding scheme.

## ABiCo in numbers

| | |
|---|---|
| **Duration** | 14.4.2024 to 31.8.2026 |
| **Total budget** | €3,370,459 |
| **Research institutions' budget** | €2,064,824 |
| **Companies' budget** | €626,635 and additional leading company (Veturi) commitment €700,000 |
| **People involved** | ~60 |
| **Publications** | 21 |

## Consortium

ABiCo brought together a broad consortium of partners. The consortium included two core industry partners (NG Nordic and Metsä Fibre), representing feedstock supply and materials development through the leading company's (Veturi) programme ExpandFibre; two innovative SMEs, Brightplus and Tonester, running parallel R&D projects; and five research organisations – VTT Technical Research Centre of Finland, the University of Eastern Finland, Lappeenranta–Lahti University of Technology LUT, LAB University of Applied Sciences, and Åbo Akademi University – responsible for high-level scientific research. In addition, five companies – Meyer Turku, Pihla Group, Syklo Biocomposites, TK-Työkalutiimi, and Vaisala – supported the project as collaborative partners.

Project preparation was facilitated by CLIC Innovation, an open innovation cluster whose mission is to enable the creation of breakthrough solutions in the bioeconomy, circular economy, and  energy systems.

## Project management

The project was organised under the scientific leadership of Kirsi Immonen, Senior Scientist (VTT), with coordination led by Kirsti Cura, Chief Specialist (LAB). The Steering Group and Work Package teams convened regularly (bi-monthly WP meetings and biannual Steering Group meetings). The Steering Group was chaired by Kirsi Hirvonen (Metsä Fibre).

The research activities were organised around three main themes: Materials and processing, Design and end-of-life solutions, and Demonstrations and feasibility. The three themes were managed by WP leaders from the research institutes. The companies took an active part in the activities of the theme groups and in guiding the project. CLIC Innovation was selected as the project coordinator through a competitive tendering process and was responsible for coordination and supporting dissemination and communication activities.

The collaboration between the companies and researchers was close. There were two specific industry workshops organised in Lahti (June 2025) and Tampere (October 2025), as well as an online workshop to explore future research ideas (Beyond ABiCo) (April 2026).

The **work package structure** is shown in Figure 1.

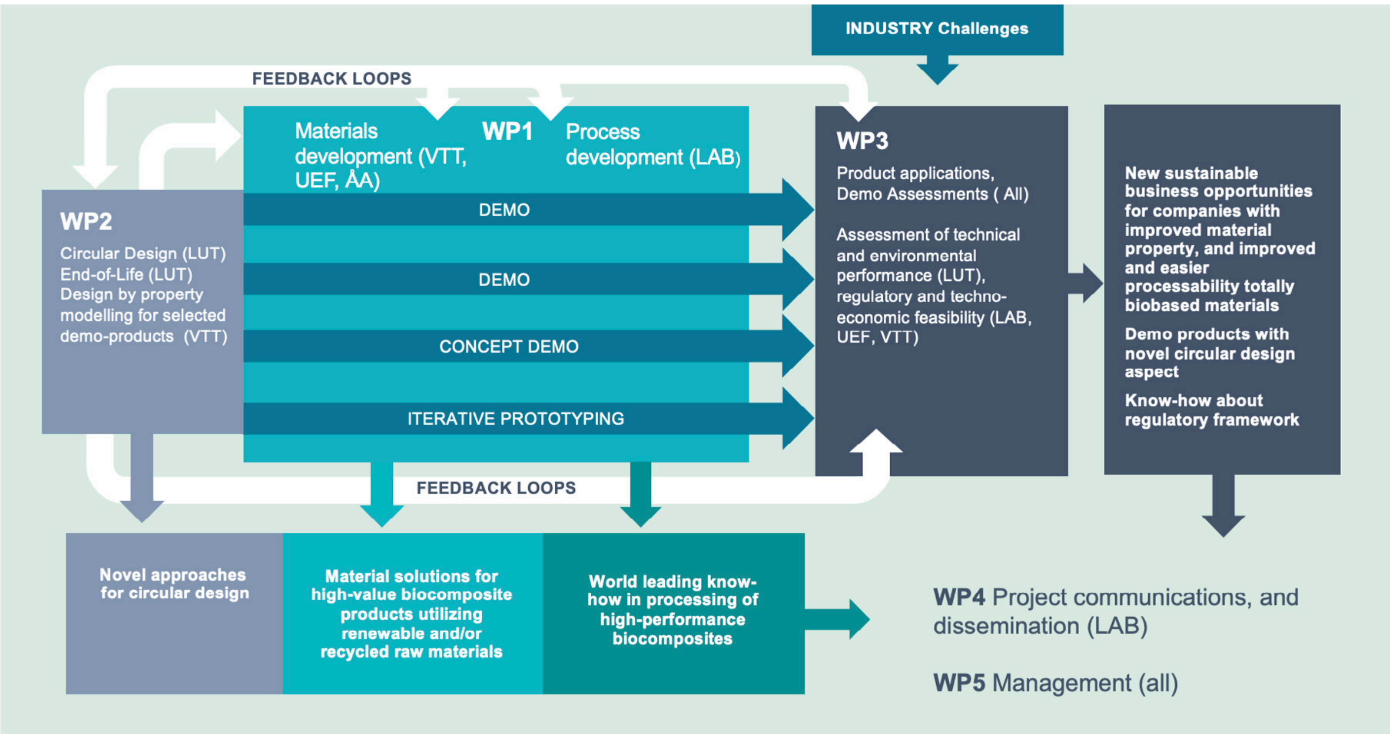


*Figure 1. ABiCo work package structure and expected areas of impact.*

## WP Leaders and Steering group

WP1 Kirsi Immonen, VTT; WP2 Mika Horttanainen, LUT; WP3 Reijo Lappalainen, UEF. Communications and dissemination activities, WP4, were led by Anu Kurvinen, LAB.

| Organisation | Member |
|---|---|
| LAB University of Applied Sciences | Ossi Martikka |
| VTT Technical Research Centre of Finland | Katariina Torvinen |
| University of Eastern Finland | Laura Tomppo |
| Lappeenranta–Lahti University of Technology LUT | Juha Varis |
| Åbo Akademi University | Carl-Eric Wilen |
| Metsä Fibre Oy | Kirsi Hirvonen, chair |
| NG Nordic Finland Oy | Kari Aaltonen |
| Brightplus Oy | Jarkko Leivo |
| Tonester Oy Ltd. | Mervi Puska |
| Meyer Turku Oy | Sani Ojala |
| Vaisala Oyj | Tuomas Nieminen |
| Pihla Group Oy | Timo Nissinen |
| Syklo Biocomposites Oy | Markku Nikkilä |
| TK-Työkalutiimi Oy | Marianne Nurminen |
| **Expert members** | |
| Business Finland | Tuomas Lehtinen |
| Business Finland | Markku Heimburger |
| CLIC Innovation Oy | Aila Maijanen |
| CLIC Innovation Oy | Taina Kujanpää |

*Table 1. ABiCo Steering group*

# Integration of circular design, life-cycle assessment, and AI-driven product development

## Summary

The research on circular design (CD), life-cycle assessment (LCA), and artificial intelligence (AI) within the ABiCo project was conducted to support the development and industrial adoption of circular biocomposite products. The work focused on integrating circular design principles, life cycle-based environmental assessment, and emerging AI-assisted approaches into material and product development processes to enable more sustainable, data-driven decision-making. By combining methodological development with industrial case studies, the research strengthened the evidence base for circular biocomposite design and supported the transition towards more sustainable manufacturing practices.

The main objective was to develop and apply practical circular design approaches that facilitate the implementation of biocomposite materials in industrial applications while ensuring their environmental performance through life cycle-based assessment. In close collaboration with industrial partners, particularly Pihla and Meyer Turku, multiple ideation workshops, company visits, and co-development sessions were conducted to identify opportunities for redesigning products, components, manufacturing processes, and broader system configurations in accordance with circular economy principles. These activities resulted in several circular design concepts focused on material substitution, lightweighting, improved recyclability, resource efficiency, and enhanced end-of-life performance. In parallel, a structured methodological framework was established linking circular economy objectives, circular design strategies, and LCA to support decision-making during product development. A systematic literature review further classified circular design strategies and examined the role of LCA in evaluating circular design solutions, while the work also contributed to the development of a biocomposite material database and the advancement of AI-assisted approaches for circular product development.

The developed methodologies were validated through industrial case studies. A detailed LCA of a wood–aluminium clad window system demonstrated that targeted substitution of conventional materials with biocomposites can substantially reduce environmental impacts, while confirming the effectiveness of selected circular design strategies. In parallel, a second industrial case study was initiated to evaluate alternative ABiCo biocomposite formulations for cruise ship handrail applications. Overall, the project delivered practical circular design methodologies, life-cycle assessment tools, industrial case studies, and supporting databases that together provide a strong foundation for the future development and industrial implementation of sustainable biocomposite products, while contributing to the integration of AI-supported decision-making into circular product development.

# Circular design integration

## Description

Circular design (CD) in the ABiCo project focuses on integrating circular economy principles into the development of biocomposite materials and applications. The objective is to enable the transition from conventional fossil-based materials towards bio-based and recycled alternatives while improving resource efficiency, product performance, and end-of-life potential. Within the project, circular design is approached as a holistic framework that considers the entire life cycle of materials and products, including raw material sourcing, processing, use phase, and end of life. Particular attention is given to the role of design decisions in influencing environmental performance, especially in material-intensive sectors such as construction and industrial applications. The work carried out under this task is closely linked to the development of circular design strategies (CDS), which provide structured approaches for improving sustainability. These include strategies related to material efficiency, use of recycled content, lightweighting, durability, and end-of-life recovery. The conceptual basis for this work has been developed through a systematic analysis of literature and policy frameworks, enabling the classification of circular strategies into functional groups and supporting their application in real case studies. Within ABiCo, circular design has been applied particularly in the context of biocomposite material development and case applications, where the substitution of conventional materials with more sustainable alternatives has been explored. The work is closely connected with LCA, which is used to evaluate the environmental implications of the proposed design solutions. The relationship between the circular economy, circular design, and LCA is illustrated in Figure 2. The circular economy defines system-level sustainability objectives, while circular design strategies represent design-level actions to achieve these goals. LCA acts as an evaluation tool, providing a quantitative basis for assessing the environmental performance of these strategies across the life cycle.

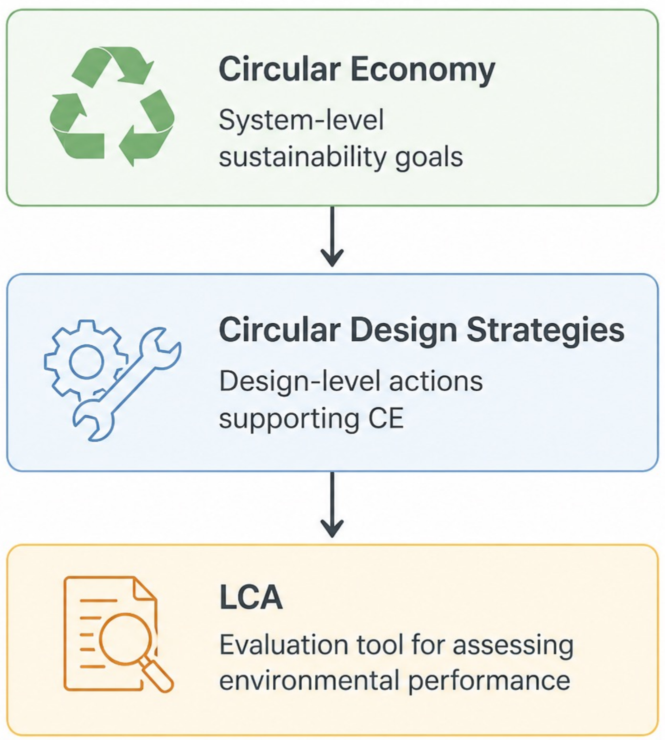


*Figure 2. Relationship between the circular economy, circular design strategies, and LCA. (Falsafi et al., 2025)*

## Results

The work shows that circular design provides a structured approach for improving the sustainability of biocomposite materials and applications, particularly through targeted material and design interventions. The analysis indicates that strategies related to material substitution and sustainable material innovation have a significant influence on environmental performance, especially when replacing high-impact materials such as metals and fossil-based polymers.

In addition, strategies focusing on resource efficiency and material optimisation contribute to reducing overall material demand, which can lead to cumulative environmental benefits at the system level. The results also highlight that circular design strategies are rarely implemented in isolation. Instead, combinations of strategies are often required to achieve meaningful improvements. For example, the use of recycled materials, combined with optimised design and improved end-of-life considerations, can provide more substantial benefits than single interventions. At the same time, the findings show that circular design does not automatically lead to improved environmental performance. Trade-offs may occur between life-cycle stages or impact categories, depending on material choices and system conditions. This underlines the importance of integrating quantitative assessment methods, such as LCA, into the design process. Overall, the work demonstrates that circular design plays a key role in guiding the development of biocomposite solutions within ABiCo, while its effectiveness depends on proper evaluation and integration with life cycle-based assessment tools.

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## Publications

Falsafi, A., Togiani, A., Colley, A., Varis, J., Horttanainen, M. (2025). Life cycle assessment in circular design process: A systematic literature review. Journal of Cleaner Production, 521, Article 146188. https://doi.org/10.1016/j.jclepro.2025.146188

# Biocomposite material database and design support tool

## Description

The biocomposite material database and design support tool was developed within the ABiCo project to improve the accessibility, organisation, and utilisation of biocomposite material data during product development and material selection processes. The objective was to support designers, researchers, and industrial stakeholders in identifying suitable biocomposite materials based on both technical performance requirements and sustainability considerations. The database integrates information from commercially available and research-stage biocomposite materials developed or investigated within the ABiCo project and its partner network. Material properties such as density, tensile strength, flexural strength, stiffness, thermal conductivity, fibre content, polymer type, and other relevant engineering parameters are incorporated into a centralised and searchable platform.

The tool was designed to function as a practical decision-support system during early-stage product development, when material selection significantly influences product performance, manufacturability, and sustainability outcomes. By providing structured access to material property information, the database supports more efficient screening and comparison of alternative biocomposite solutions, and reduces one of the major barriers to industrial adoption of emerging sustainable materials. In addition to supporting material selection, the platform provides a foundation for future integration of circularity indicators, life-cycle information, and advanced digital design tools. The database therefore contributes to the broader objective of enabling data-driven and sustainability-oriented product development within circular economy applications.

## Results

The development of the database resulted in a centralised repository of biocomposite material information that improves the availability and usability of material data for engineering applications. The system enables users to efficiently compare alternative material options and identify candidate biocomposite solutions based on targeted performance requirements. The database demonstrates how digital tools can support the implementation of circular and sustainable materials in industrial product development by reducing the effort required to access and evaluate material information. The platform facilitates more informed material selection decisions and promotes greater visibility of emerging biocomposite solutions among industrial users, researchers, and product designers. The work also established a scalable framework that can be expanded beyond the scope of the ABiCo project. Future development may include the integration of life-cycle assessment indicators, circularity metrics, environmental product information, AI-assisted material recommendation functions, and larger material libraries. Such developments would further strengthen the role of the database as a comprehensive decision-support tool for sustainable and circular product development. Overall, the database represents an important practical outcome of the ABiCo project by supporting the translation of material innovation into industrial implementation and by improving the accessibility of information needed for the wider adoption of biocomposite materials.

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# Life-cycle assessment of a window case

## Description

LCA was applied within ABiCo as a quantitative decision-support tool for evaluating the environmental performance of biocomposite materials and circular design solutions. The primary objective was to assess whether proposed material substitutions and circular design interventions result in measurable environmental benefits across the product life cycle. A completed case study focused on a wood–aluminium clad window system developed by Pihla. The assessment investigated the environmental implications of replacing selected conventional components, including aluminium cladding, PVC glass holders, and Zamak handles, with biocomposite alternatives based on recycled polypropylene reinforced with cellulose fibres. As shown in Figure 3, the analysis covered raw material extraction, manufacturing, transportation, and end-of-life stages, including recycling and energy recovery scenarios. The study was designed to evaluate the environmental performance of circular design strategies identified during the circular design activities, particularly sustainable material innovation, material substitution, resource efficiency, and increased use of recycled materials. In addition to the completed window system assessment, the second LCA study is currently ongoing within ABiCo. This work focuses on cruise ship handrail applications and evaluates alternative biocomposite formulations developed within the project. The assessment compares different combinations of polymer matrices, reinforcement materials, recycled content levels, and chemical additives, including fire-retardant and weather-resistance additives. The objective is to quantify the environmental contribution of individual material components and support the identification of environmentally preferable biocomposite formulations for future industrial applications.

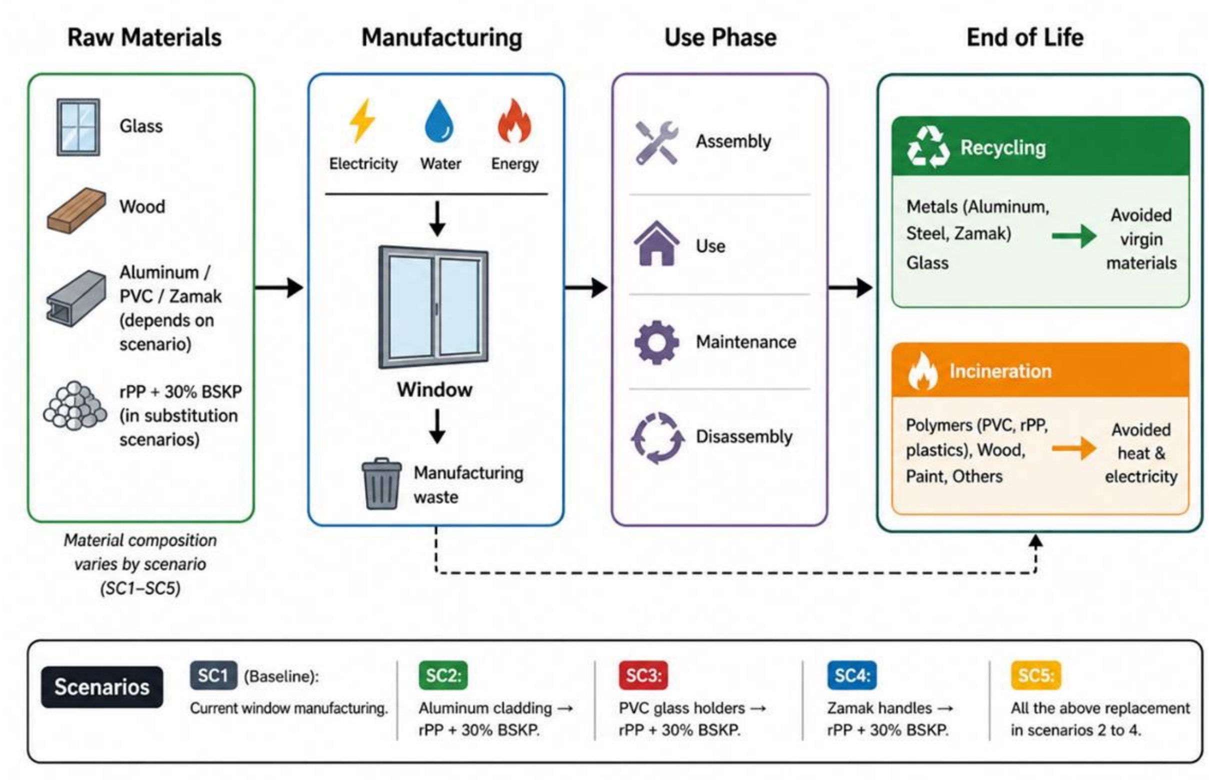


*Figure 3. LCA system boundary and circular design material substitution scenarios (SC1–SC5) assessed for the window system.*

## Results

The window case study demonstrated that targeted biocomposite substitutions can significantly reduce environmental impacts while supporting circular design objectives. The results showed that replacing selected high-impact components with biocomposite alternatives resulted in reductions of up to approximately 40% in key environmental impact categories, particularly climate change and fossil resource use. The assessment validated several circular design strategies identified within the project. Sustainable material innovation was validated through the replacement of conventional materials with biocomposites. Material substitution and increased use of recycled materials contributed to reductions in fossil resource consumption and life-cycle greenhouse gas emissions. Resource efficiency strategies were also supported through reductions in material demand and optimisation of component design. The results further demonstrated that environmental performance is strongly influenced by a limited number of materials, particularly aluminium and fossil-based polymers. Consequently, material selection was identified as one of the most influential design decisions affecting life-cycle impacts. The study also highlighted the importance of considering end-of-life management, recyclability, and waste treatment pathways when evaluating circular solutions.

The ongoing handrail study is expected to provide additional insights into the environmental performance of alternative ABiCo material formulations. By comparing different polymer matrices, reinforcement materials, recycled content levels, and functional additives, the study will identify the main environmental hotspots within biocomposite formulations and support environmentally informed material development. The results will provide guidance for selecting material recipes that achieve an optimal balance between technical performance, regulatory requirements, and environmental sustainability.

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## Publications

Falsafi, A., Togiani, A., Abdulkareem, M., Faludi, J., Varis, J., Horttanainen, M. (2026). Life cycle assessment of biocomposite material substitutions in window frames to implement circular design approach. https://doi.org/10.1016/j.enbuild.2026.118074

# Towards AI-aided circular product design

## Description

Circular product design poses an engineering integration challenge across material development, component design, manufacturing processes, process equipment, and system-level assessment of circular strategy, technical performance and economic feasibility. Experiences from the ABiCo project were used to illustrate why circular materials require co-development of products, processes, process equipment, quality control, and life-cycle information. AI tools were used transparently to support summarisation, synthesis, and drafting of the text, while the authors remain fully responsible for the content, interpretation, and conclusions.

The transition to a circular economy requires products and manufacturing systems to support multiple life cycles, value retention, and lower environmental impact, alongside technical and commercial objectives. However, circular feasibility is determined by detailed engineering choices in materials, geometry, joining, manufacturability, reliability, compliance, and life-cycle data. The choices often affect each other. The challenge is strongest during early design, when key decisions are made before the actual material behaviour, geometry-specific manufacturing quality, component-level performance and life-cycle outcomes are known, relying on model-based decision-making. Bio-based and recycled materials increase this uncertainty of end-product performance, because their properties and processability may vary more than those of conventional materials.

The proposed approach links circularity targets – such as durability (for life-time extension), lightweight design (for reduction of energy consumption and emissions), repairability, reuse, remanufacturing, and recyclability – to concrete engineering decisions. It combines physics-based simulations, monitored process and material data, AI-based surrogate models, inverse analysis, system-level evaluation, and predictive life-cycle assessment. This enables requirement-driven model-based design that considers performance, manufacturability, circularity, uncertainty, compliance-by-design, and traceable life-cycle information.

## Results

The causal structure behind biocomposite product development is summarised in Figure 4. The fishbone diagram links material composition, manufacturing processes, component design, geometry effects, and resulting properties and reliability of the end-product. Identifying the most influential factors enables efficient AI modelling, which can support predictive decision-making and inverse design: material compositions, process settings, and component geometries can be explored against target requirements, and identified control factors enable the achievement of the target quality and reliability despite feedstock variability, using robust design methods.

Circular product design is also shaped by system-level interactions, as illustrated in Figure 5. Material and circular-strategy choices affect dimensions, assembly, reliability, manufacturing, and feasible life-cycle options, while engineering solutions and positive system-level reinforcement loops may enable higher-value circular strategies. Technical performance, sustainability performance, regulatory demands, and scalability are therefore interdependent design concerns.

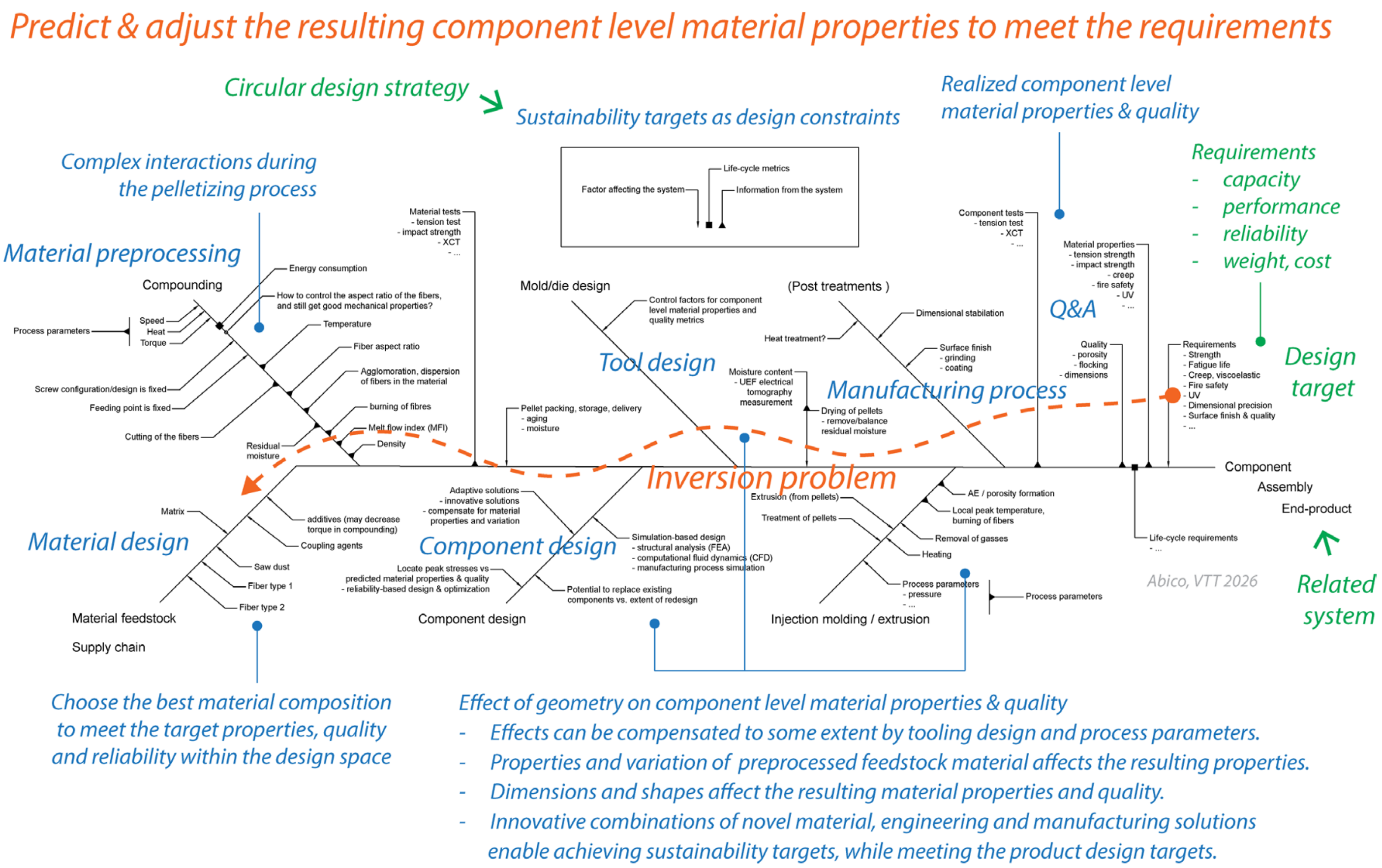


*Figure 4. Causal chain linking material, process, and component performance for AI-aided inverse design.*

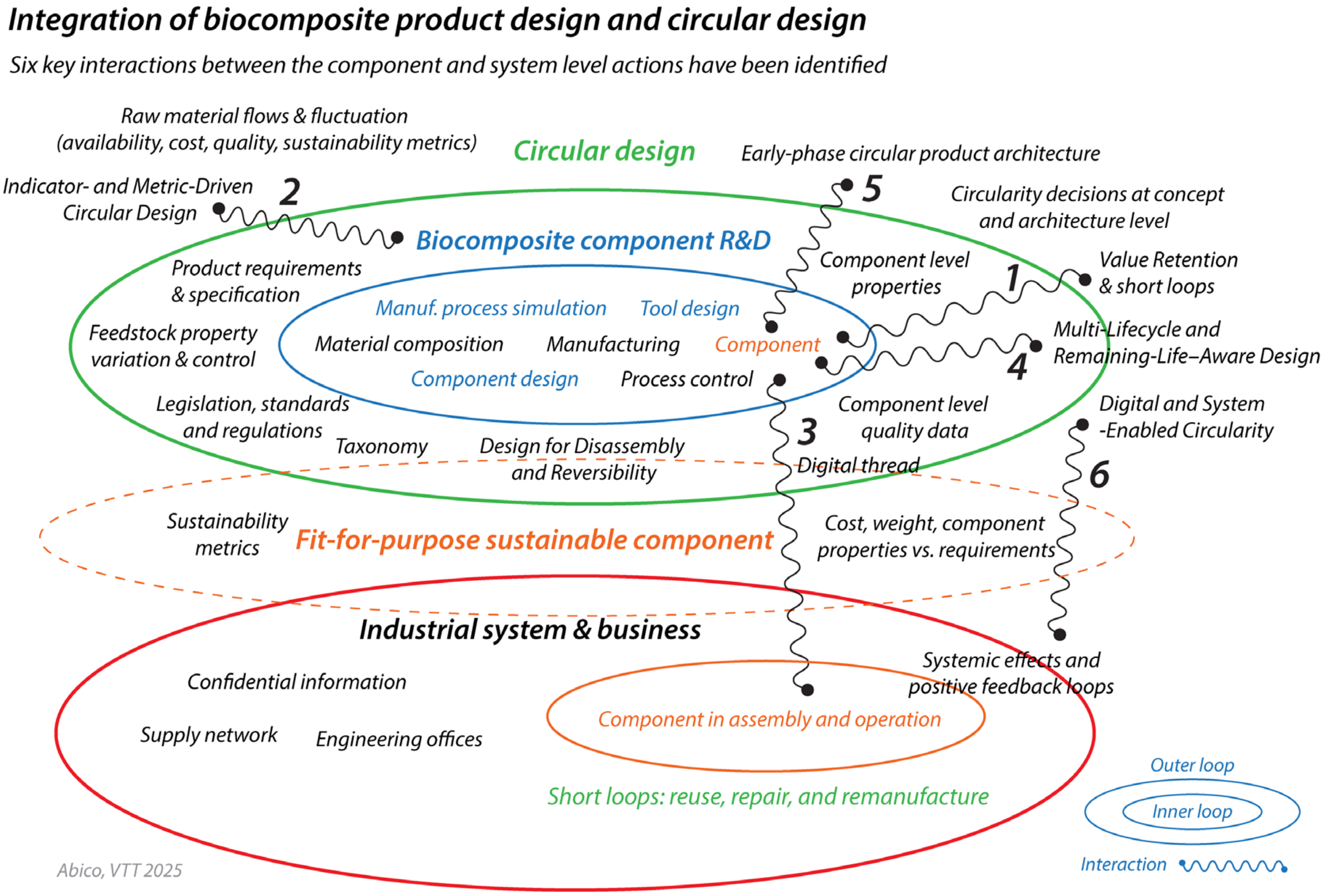


*Figure 5. Component- and system-level interactions in circular product design.*

The main finding is that circularity assessment should be embedded into early design decisions instead of added downstream, and the interactions of various factors affecting design need to be considered. Sustainability objectives should be treated as primary design drivers and linked directly to engineering choices. Uncertainty should also be treated explicitly: emerging materials and processes should be evaluated using simulations, parametric analysis, surrogate models, and scenario-based sustainability assessment to identify robust solution spaces and clarify trade-offs between performance, manufacturability, circularity, and compliance. The ABiCo project confirmed this need in practice. Material variability, fibre degradation, and limited compatibility with existing manufacturing equipment can constrain industrial uptake even when sustainability potential is high. Circular implementation therefore depends on co-development of materials, processes, equipment, quality control, and life-cycle data management. The proposed framework connects component-level circular product design models with system-level circular design decisions. It combines physics-based simulation, use of monitored data in training AI models, AI-based surrogate models, inverse analysis, and predictive LCA in an iterative modelling architecture that keeps design intent, uncertainty, and life-cycle implications connected. Product design, manufacturing design, and sustainability assessment could therefore be treated as linked decisions rather than separate tasks.

A key benefit of the proposed framework is that sustainability and circularity assessment become part of design exploration. Predictive LCA can be used with engineering simulations to reveal environmental drivers and trade-offs early enough to influence concept selection and architecture decisions. Identification of system-level reinforcement loops and application of novel engineering solutions support making circular strategies technically and commercially feasible.

Feedstock variation and uncertainty should be treated as design variables. Robust product and process design, supported by surrogate models and inverse analysis, can identify feasible regions in the parameter space that tolerate variability in materials, processing, and operation. For bio-based materials, this can be achieved by developing adaptive process equipment, using process and operational monitoring, model-based process control, and multi-objective optimisation of end-products.

For industrial implementation, the framework can reduce late redesign, improve manufacturability, and support higher-value circular strategies such as reuse, refurbishment, and remanufacturing. It also aligns development with regulatory expectations for traceable life-cycle data, demonstrable sustainability performance, shared digital models, industry renewal, and continuous learning across circular value chains.

In conclusion, circular design should be approached as a multi-level engineering task that links material development, component/product design, manufacturing process and process equipment development, systemic effects, and evaluation and choice of circular strategies in circular product development. The proposed AI-aided framework supports early decision-making under uncertainty, connects sustainability goals to engineering evidence, and helps make circular solutions industrially practical. Future work should focus on integrated modelling, adaptive manufacturing with embedded sensoring for efficient collection of AI training data, life-cycle data infrastructure and data management, and validation in industrial product-development cases.

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# Materials and process development


## Summary

In the materials and process development work package, the ABiCo project investigated bio-based fillers and additives in mainly polyolefin-based bio-composites with polymer matrices, such as recycled CIRCO PP from NG Nordic and bio-based LDPE. From thermoplastic processing methods, extrusion, injection moulding and 3D printing were studied, as well as foamability of biocomposites in joint work with the Portuguese research organization PIEP. For 3D printing, a totally bio-based compound was prepared using polylactic (PLA) as a polymer matrix and sawdust side-stream from Pihla. The second filler material in the research focus was bleached softwood cellulose fibre from Metsä Fibre. That has challenges related to proper feeding and modification procedures before compounding, so the development of the fibre pre-processing was also studied at VTT.

The aim in ABiCo was to develop sustainable, safe and industry-relevant material solutions for long-life-time applications requiring weather resistance and flame retardance properties. Novel flame retardance systems for biocomposites were developed at Åbo Akademi and UEF provided renewable-based ther-mochemical side-streams such as biophenols, biochar and distillates for the project purpose, together with their safety assessments.

In conclusion, the ABiCo project was able to show the potential of novel additives in providing improved hydrophobicity, processability, flame retardance, and mechanical and thermal performance. Finally, meta-analysis showed the most promising product categories for biocomposites and that the bottlenecks in biocomposites are not typically related to individ-ual material parameters, process steps or compo-nent solutions, but to the connections between these factors, where early phase AI and circular design can provide significant help.


# Distillate preparation

## Description

Thermochemical techniques, such as slow pyrolysis or hydrothermal liquefaction (HTL), provide efficient ways to convert biomass to solid, liquid and gas outputs. Slow pyrolysis (A. Salami, 2021) is especially suitable for relatively dry biomass (moisture content below 20%) with typical heating rates of 3-80°C/min and a maximum temperature of 350-750°C depending on a specific equipment and biomass particle size. The yield of condensable gases (distillates) is 30-45%, and of solid products 35-50% (dry basis weight).

Although the liquid components of wood have many potential applications, large volumes of liquids are still being discarded or burned and not exploited in industrial applications. Thus, the incorporation of more wood distillates into biocomposites would enhance the use of bio-based raw materials and secondary products from the wood-processing industries in a sustainable manner. Based on earlier results (T. Vaisanen, 2016), both hardwood and softwood distillates exerted positive effects on the water resistance of the wood–plastic composites (water absorption decreased 16-25%), as well as on tensile strength (increased 5-11%). Furthermore, the injection moulding process performed better, probably due to distillates acting as a lubricating agent. Therefore, we wanted to test this concept with the novel biocomposites studied in ABiCo.

## Results

Foam-formed BSKP sheets were dried, weighed and treated using distillates from hardwood (HWD) and softwood (SWD). The sheets were chopped and used as fibre reinforcements in bio-LDPE and PP-Circo to a fibre content of 20%. The final distillate content in the compounds was 1.6% (HWD and SWD) and 2.8% (SWD) fibre, corresponding to 8% and 14% in the sheets. An example of the prepared composite materials is presented in Figure 6.


*Figure 6. PP-Circo and bio-LDPE biocomposites with 20% BSKP fibres treated with distillates from hardwood (HWD) and softwood (SWD*

Results for the composites show very even fibre dispersion without visual agglomeration. In PP-Circo, the distillate-treated cellulose showed mainly a plasticization effect and, due to that, slightly reduced mechanical strength properties. The plasticization effect was seen in a 2.5 to 6 times increased MFI value compared to BSKP-containing composites without distillate treatment. In bio-LDPE composites, the distillate-treated BSKP fibres provided a 14 to 20% improvement in impact strength properties compared to BSKP fibres without treatment. Effects such as those with PP-Circo were also found for MFI in bio-LDPE based compounds. Part of the strength improvement most probably originates from improved fibre dispersion. There is a publication in preparation related to these results.

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## References

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# Biophenols for composites

## Description

Phenols are a diverse group of compounds that have been conventionally produced from fossil-based sources by refining tar, naphtha, and so on, and used for plastic and resin manufacturing or as reagents and even in pharmaceutical and medical products. However, phenolic compounds are formed in plants, and they can be processed from lignocellulosic biomass using thermochemical techniques, since they are formed especially as degradation products of lignin. In this project, we utilised slow pyrolysis to produce distillates from birch and then applied a scalable CPC technique to separate and purify different phenol fractions at lab scale for characterisation and testing (N. Jokinen, 2025).

In the case of biocomposites, biophenols can have multiple roles, such as contact agents, reaction enhancers for bonding, antibacterial or antifungal agents, or antioxidants or UV-stabilizers during material aging. Furthermore, bio-based phenols may provide sustainable replacements for petroleum-derived phenols in biocomposite matrices.

## Results

As a large set of different slow pyrolysis and hydrothermal liquefaction liquids were analysed by 1H NMR spectroscopy, it turned out that birch-based distillate fractions provided a good rich alternative (4-5 wt%) for separation of different phenols. CPC separation experiments were performed by a pilot-scale CPC-PLC purification system (Gilson Inc., WI, USA), as shown in Figure 7, using proper solvent systems. Purified phenol fractions collected in tubes were typically mixtures of 3-4 methoxyphenol components (Figure 8).

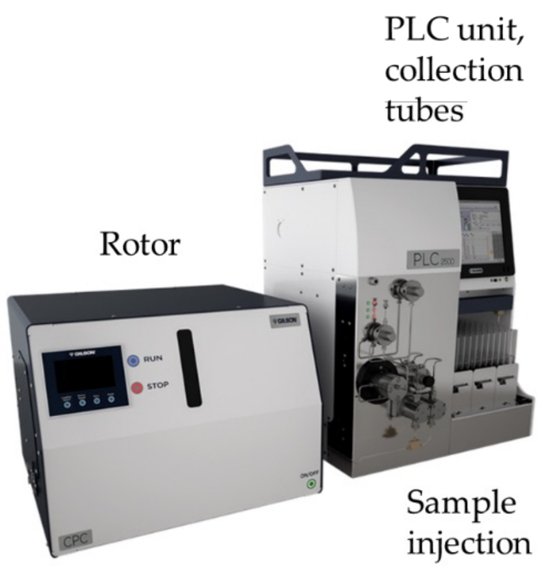


*Figure 7 Purification system*

*Figure 8 Purified phenol fractions in tubes*

The collected phenols were pooled into five different types of phenolic mixes with purity greater than 70%. The purified biophenol yield was 0.15 – 0.25 wt% from original dry wood biomass. With this lab-scale equipment, it was possible to purify a few tens of grams of phenols for characterisation and preliminary testing in composites and coatings, for example to test antimicrobial properties, toxicity, and VOC emissions.

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## Publications

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# Biochar in composites

## Description

Biochars are relatively affordable bio-based materials that can be produced using different biomasses or industrial side streams, for example by using thermo-chemical slow pyrolysis processing (A. Salami, 2021). At relatively low concentrations (<10 wt%), they could enhance the mechanical properties of bio-based polymer composites (tensile strength, flexural modulus or microhardness), thermal stability, and UV resistance. Furthermore, biochar in composites acts as a carbon sink, and it may provide electrical conductivity or electromagnetic shielding when processed properly.

Two types of biochars were prepared using slow pyrolysis from birch (pieces of firewood) and hemp (hurd). After slow pyrolysis processing, both of them were heat-treated at 600°C for 2 hours and ground to particle size below 100 µm. The carbon content for these high quality biochars is >85 wt%, and the active surface area (BET) is about 290 $m^2/g$.

## Results

Biochars were introduced in the bio-LDPE-BSKP composite as an additive in amounts of 4%. Figure 9 presents biochar-treated BSKP-fibres and injection-moulded composites. The relative results for the composites are presented in Figure 10.

*Figure 9. Biochar-treated BSKP fibres (left) and composites with 4% of BC1 and BC2 (right)*

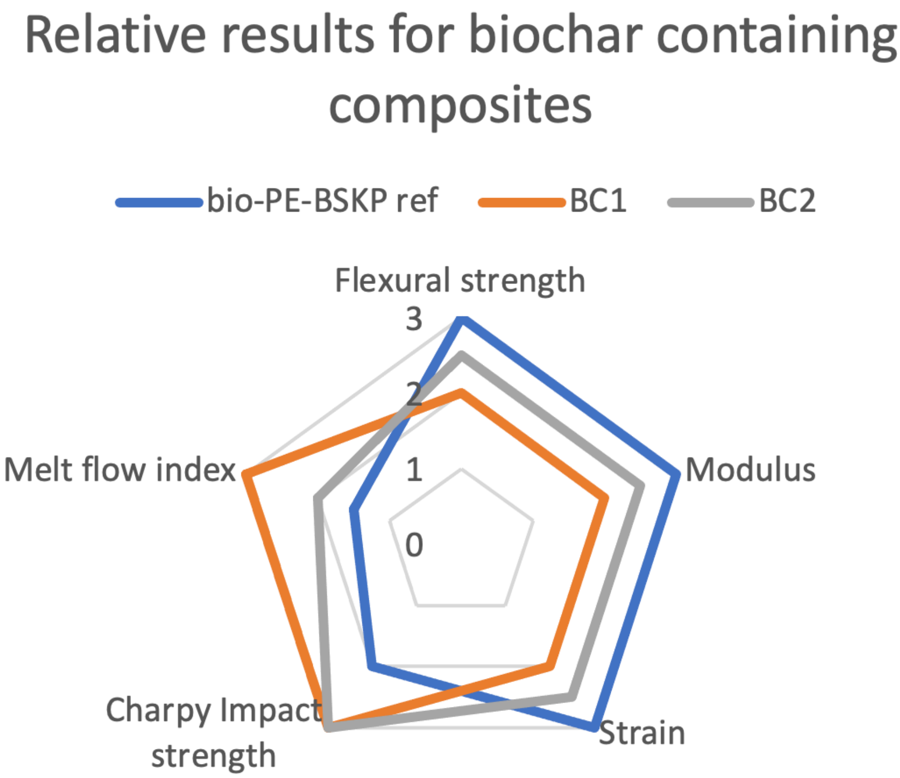


*Figure 10. Relative results for biochars BC1 and BC2 containing LDPE-BSKP composites.*

Even the small 4% addition of biochar has a significant effect on biocomposite properties. Most visual was the colour change to deep black. For processability, the biochar provided lower melt viscosity for the BSKP-fibre composite, enabling easier injection moulding.  In terms of product properties, biochar provided enhanced impact strength but a slight reduction in modulus and flexural strength properties, making the composite more flexible compared to material without biochar. The effect on long-term properties is presented in Chapter 4.

A publication related to biochar composites is under preparation.

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## References

A. Salami, Biorefining of lignocellulosic biomass and chemical characterization of slow pyrolysis distillates, dissertation, University of Eastern Finland, 2021.

# Biocomposite materials, processing and testing methods

In the ABiCo project polymer selection, the main criteria were to use recycled, recyclable and potentially bio-based polymer matrices enabling a circular design approach and use in long life-time applications. The polymer raw materials for biocomposites were post-consumer recycled polypropylene Fortum CIRCO® PP 22-1000 from NG Nordic with a melt flow index (MFI) of 22 g/10 min (@190°C and 2.16 kg), and bio-based low-density polyethylene SPB608 from Braskem with an MFI of 30 g/10 min (@190°C and 2.16 kg). Bio-based and industrially biodegradable polylactic acid Luminy® L175 from Total-Corbion was used as a polymer matrix in the 3D-printing compound. That polymer is more suitable for extrusion, with an MFI of 3 g/10 min (@190°C and 2.16 kg). Fibre reinforcements were selected according to good availability and reinforcing potential, as well as based on availability within the consortium. Two different types of fibres were selected: bleached softwood kraft cellulose (BSKP) from Metsä Fibre's Rauma mill and sawdust (SD) type side-stream from Pihla's window production process. BSKP fibre is pure cellulose fibre without lignin, with an average fibre length and width of 2.5 mm and 30 µm, respectively (Asad et al. 2025). Side-stream SD had mixed wood fractions and pieces of different sizes, containing all the main wood ingredients: cellulose, hemicellulose and lignin, and potentially also some bark fractions. After milling, SD was more like particles than fibres.

The ABiCo project materials compared to existing biocomposite Elastopoli (currently SYKLO) provided commercial reference biocomposite materials are PE+20% cellulose fibre (PE20) compared to PP+30% cellulose fibre (PP30).

BSKP fibres were obtained in never-dried form containing 70 wt% moisture and in the form of large lumps that could not be introduced in compounding processes as such. So, they had to be treated in a form more suitable to the automatic screw

*Figure 11. Compactor device (left and middle pictures) and BSKP fibres after compacting (right picture).*

feeders typically used in plastic processes. Three different approaches were used for BSKP pretreatment: a compacting method, batch mixing, and foam forming. The compacting method used a compactor device developed and patented at VTT, enabling it to pelletize moist fibres into pellets suitable for feeding into the compounder presented in Figure 11 (left and middle pictures). BSKP fibres after treatment are shown in Figure 11 (right picture). Batch mixing used a Forberg Twin Shaft Baddle Batch-mixer F-OC (Forberg International AS., Lervik, Norway), which was able to break the pulp lumps into small, dense agglomerates, as presented in Figure 12.

In the foam forming route, the BSKP fibres were prepared as 500 gsm pulp sheets, which were dried and cut into pieces suitable for feeding into the compounder. The procedure and cut pieces are presented in Figure 13.

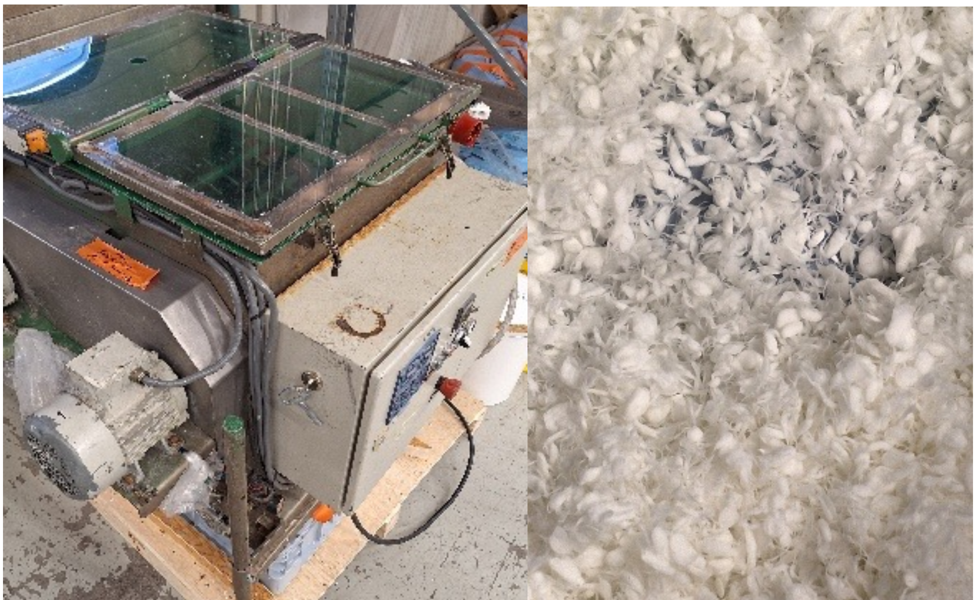

*Figure 12. Batch-mixer and BSKP fibres after the mixing procedure.*

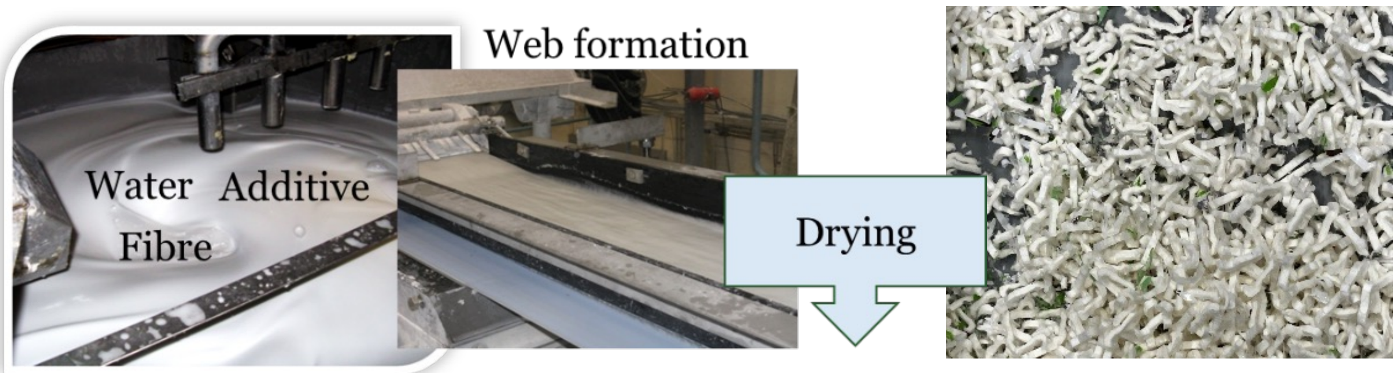


*Figure 13. Foam forming of BSKP fibres (left) and cut pieces from the BSKP sheet (right).*

Side-stream SD from Pihla had to be milled before preparing compounds. Milling used a Rivakka hammer mill (Nipere Oy, Teuva, Finland) with a 2 mm sieve, providing fine sawdust easy to feed into the compounder, as presented in Figure 14.

Biocomposite compounding was done using a Berstorff ZE 25x33D co-rotating twin-screw extruder (Berstorff GmbH, Hannover, Germany) with gravimetric feeders. The compound was cooled on an air-cooled belt with a cutter/granulator at the end. Compounds were injection-moulded into dog-bone shaped test pieces according to standard ISO 527, using a Smartpower 60 injection-moulding machine (Wittmann Battenfeld GmbH, Kottingbrunn, Austria). The equipment is presented in Figure 15.


*Figure 14. Rivakka hammer mill (left) and milled sawdust (right).*


*Figure 15. Compounder used for biocomposite compounding (left) and injection-moulding machine (right).*

**The prepared biocomposites were tested in several ways. The main test methods were as follows:**

- Melt flow index (MFI) for compounds using an Industrial Physics RAY-RAN Melt Flow Indexer, Model 3A (Industrial Physics, Theme, UK) according to ISO 1133-1:2011 at 190°C and 2.16 kg load.
- Differential scanning calorimetry (DSC) by NETZSCH DSC 204F1 Phoenix 240-12-0287-L (NETZSCH GmbH, Selb, Germany) to analyse thermal behaviour and crystallinity of compounded materials. A 10°C/min heating/cooling rate was applied to samples of at most 6 mg: first heating from 0°C to 200°C, then cooling to 0°C, and then heating again to 200°C.
- Density measurements were performed using an Ultrapyc 5000 helium gas pycnometer (Anton Paar GmbH, Graz, Austria) at room temperature. Sample volume was determined by helium displacement, and density was calculated accordingly. For each formulation, measurements were conducted three times, and mean values were used for analysis.
- HDT was measured according to the ISO 75 standard using method A with 1.8 MPa stress on the sample. HDT was determined using the Ceast HDT 3 VICAT P/N 6911.000 (Ceast S.p.a., Torino, Italy) for three parallel samples.
- Dilatometer coefficient of thermal expansion was measured using a Linseis L75 VS 1600 vertical dilatometer (Linseis Messgeraete GmbH, Selb, Bavaria, Germany) according to the guidelines in ASTM standard E228-22.
- Flexural strength testing using an Instron 4505 Universal Tensile Tester with a crosshead rate of 5 mm/min, and a 10 kN load cell (Instron, Norwood, MA, USA). The strain was measured using an Instron 2665 Series High Resolution Digital Automated Extensometer in compliance with ISO-178 standards. For each material, six measurements were performed after conditioning at 23°C and 50% relative humidity for a minimum of 5 days.
- Charpy impact strength tests in accordance with ISO-179 guidelines using a Charpy Ceast Resil 5.5 Impact Strength Machine (CEAST S.p.a., Torino, Italy). Testing in a three-point bending configuration for 10 unnotched samples per material, after conditioning as above.
- Tensile strength testing was carried out using an Instron 8874 dynamic mechanical tester (Instron, Norwood, MA, USA). The test speed was 1.0mm/min and the strain was determined from the gauge length, based on crosshead displacement. During the test, an acoustic emission sensor was attached to the bottom part of each sample with a clamp.
- Limiting oxygen index (LOI) was measured using Oxygen Index Module apparatus from Fire Instrumentations and Research Developments according to the ASTM D 2863 standard
- Cone calorimetry analyses were conducted to characterise the burning behaviour under forced flaming conditions according to the ISO 5660-1 standard. The cone calorimeter (FTT, UK) was operated at a heat flux of 50 kW/m2.
- Vertical flammability test (UL94) was performed in a UL94 chamber according to the eponymous standard.
- Scanning electron microscope (SEM) imaging of fractured cross-sections of biocomposites was performed using a JEOL JSM T100 SEM (JEOL Ltd., Tokyo, Japan). A sputtered gold layer of 50 nm was applied to avoid charging.
- Water absorption was tested according to ISO 62:2008 using pieces cut from injection-moulded dog-bone shaped test pieces with dimensions 2 x 2 x 0.4 cm and sandpaper-polished edges. The samples were soaked in water at 23°C temperature. Samples are weighed after 24 hours, 1 week, 2 weeks, 4 weeks and every month until the weight gain is stabilised. Weight gain and area change are reported as percentages.
- X-ray computed tomography was performed using a Nikon XTH 225 system in cylindrical mode. Images were acquired with a tube voltage of 90 kV, 10 W, 10.0 µm pixel size, and no beam filter. The data was analysed using a CT Analyser v1.25 (Bruker microCT, Kontich, Belgium) from binarized images, and the region of interest was 23 mm in height.

Extrusion process testing was carried out using a single-screw laboratory extruder (Brabender Plastograph, screw diameter 19 mm, L/D 24). The equipment is presented in Figure 16.

Filaments for 3D printing testing were produced using 3Devo's Filament Maker One. The targeted filament diameter was 1.75 mm. Temperatures used were 160, 160, 1870 and 180°C (zone 4/3/2/1 = nozzle).


*Figure 16. A laboratory-scale single-screw extruder for extrusion process evaluation. (Image Kirsti Cura)*

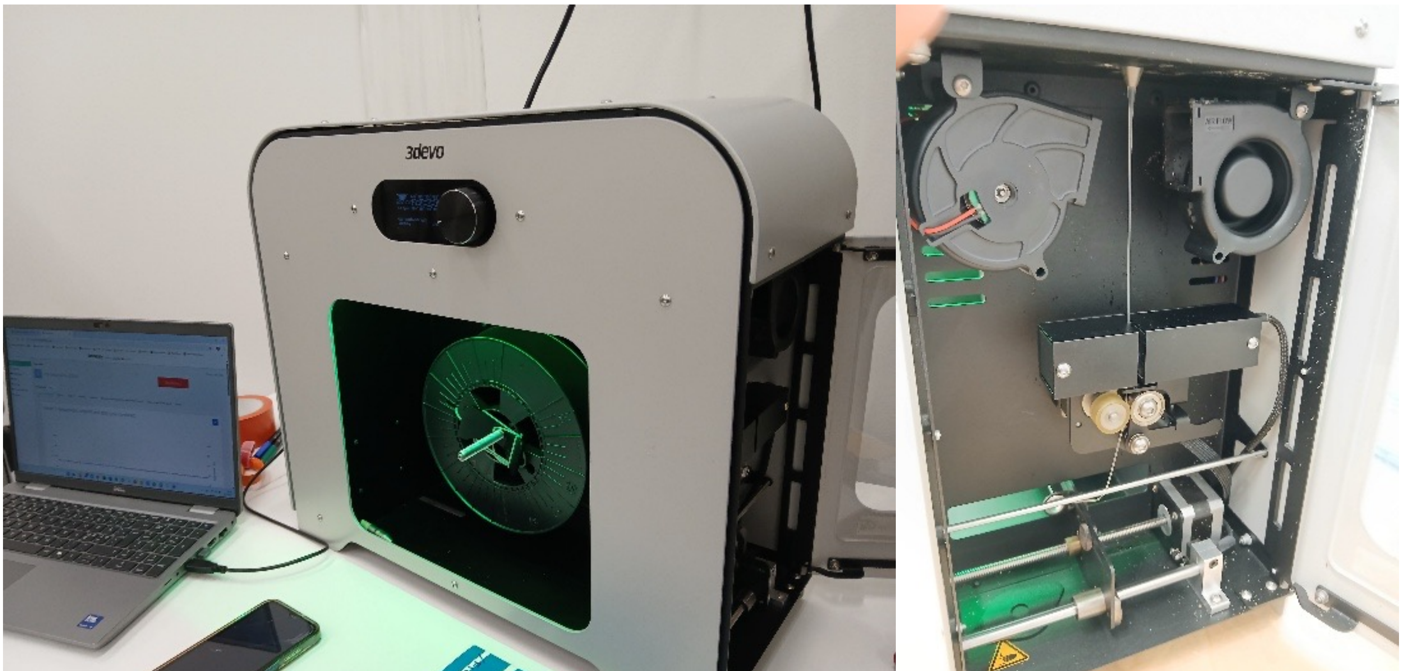


*Figure 17. A filament extruder for making 3D printing filaments. (Image Kusti Ruokamo)*

All 3D printing was carried out using the Original Prusa i3 MK3 3D printer. The nozzle diameter was 0.8 mm. Layer height was 0.3 mm. The printing temperature was 215°C for the first layer and 210°C for other layers. The print bed temperature was 60°C. The print bed was a standard Prusa PEI coated steel plate.

Impact tests for 3D-printed test bars were performed using an IZOD mechanical impact tester. The cross-sectional dimensions of the sample were 10 mm x 4 mm, in line with ISO 527. The area of the test piece was 40 mm2. The maximum impact energy of the tester is 2.65 J.

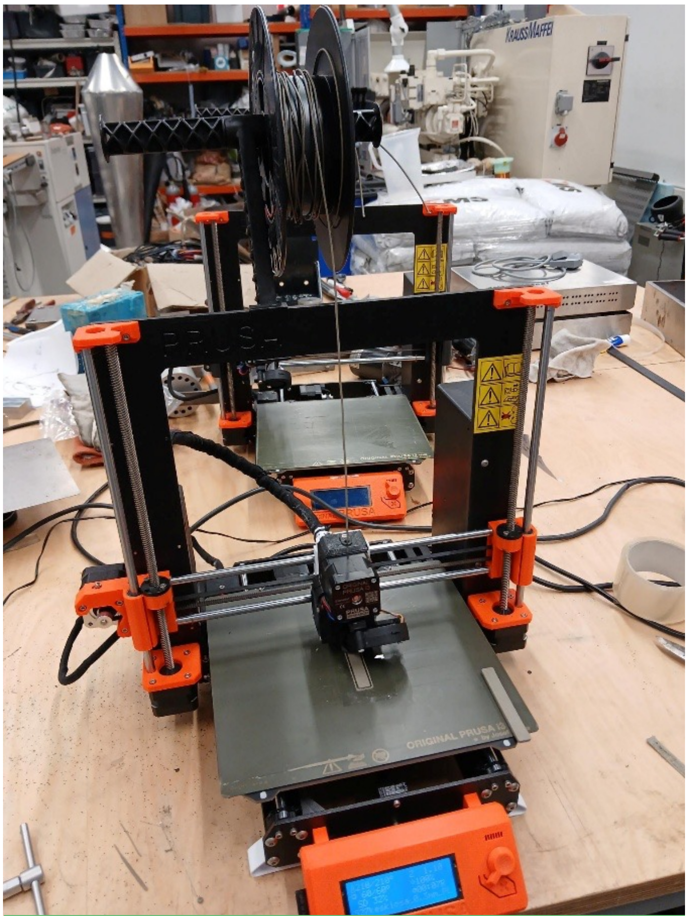

*Figure 18. A laboratory-scale 3D printer printing a test bar in the vertical direction. (Image Kusti Ruokamo)*

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# Effect of different cellulose fibre pre-treatments

One of the aims of ABiCo was to study different methods for BSKP fibre addition into the compounder. The main method was compacting of moist fibre pulp in 30% dry material content into pellets followed by drying. The second method was to use a batch mixer to mix the moist pulp until it formed small agglomerates suitable for the feeding system. The third method was to form a uniform fibre sheet using the foam forming method. Sheets of 500 gsm were only dried, and no densification by pressing was used. The dry sheets were then cut into smaller, roughly 2 mm diameter pieces with a length of 1 cm, using a sheet cutter. The methods and form of BSKP before feeding are presented in the Processing chapter.

## Results

The comparison of each measured result from injection-moulded 20% BSKP fibre containing LDPE biocomposites is presented in Figure 20 and the test samples in Figure 19. Figure 19 shows the best fibre dispersion in samples with foam formed fibres. From a fibre dispersion point of view, batch mixing treatment and compacting provided results comparable to each other.

Figure 20 shows the test results relative to each other for materials with three different fibre treatment methods. Despite having the best dispersion, the foam forming route also provided the lowest melt viscosity (highest MFI), which can have an effect on better processability in injection moulding. Thermal stability in the form of HDT and flexural strength properties was best when batch-mixing was used. The compacting method provided the highest Charpy impact strength properties.

Compacted Batch mix Foam formed

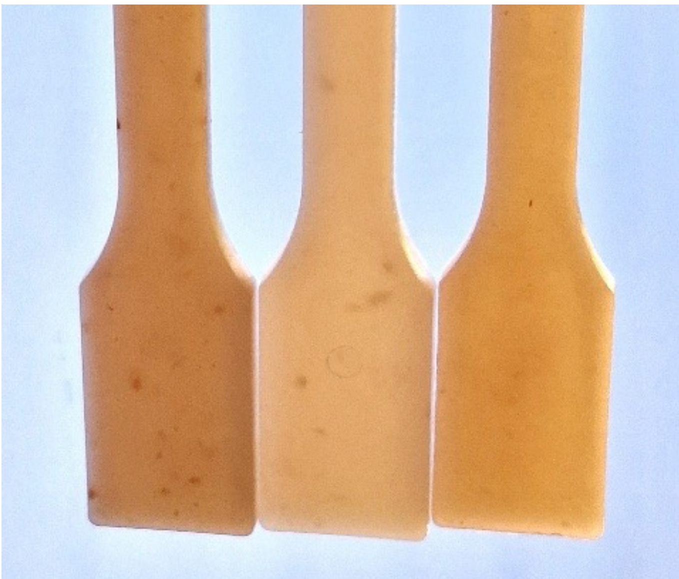

*Figure 19. Injection-moulded bio-LDPE samples with 20% BSK fibres pre-treated in three different ways: compacting method, batch mixing, and foam forming.*

When thinking of fibre modification with water-sensitive liquid additives before the compounding process with a plastic matrix, both the batch-mixing and compacting routes seem feasible methods. In the fibre feeding for plastic process, compacted or shredded foam formed fibre sheets were slightly easier to feed than batch-mixed fibres using a normal twin-screw plastic feeder. If fibres need very homogeneous treatment, and probably a covalent connection between additive and fibre, the foam forming method looks very positive for that purpose.

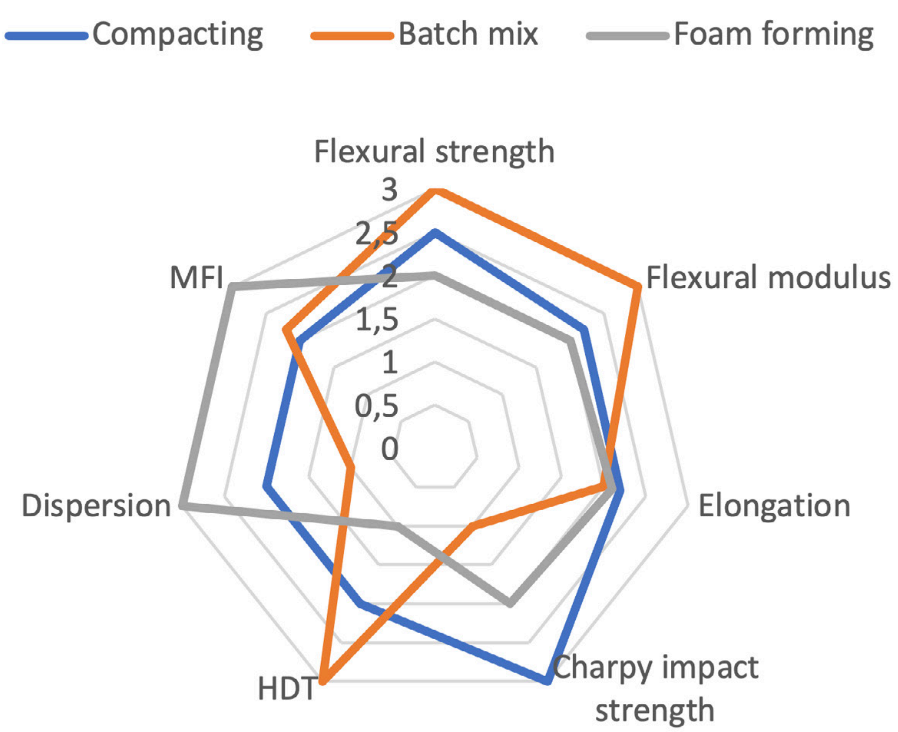


*Figure 20. Relative performance of biocomposites with different fibre pre-treatment methods.*

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# Biocomposites with hydrophobic additives

One of the challenges of hydrophilic fibres containing biocomposite materials is absorption of water that can cause, in the ultimate case, strength reduction, microbial growth and material degradation, as well as creep fractures when loaded. In many extruded materials, the fibre content is typically over 50% but can be as high as 80%. If the product is not coated, some of the fibres are most probably on the surface and susceptible to moisture absorption in outside applications and long-term use. To minimise the moisture effect, two different approaches were taken. The first was to use a more common way of using the compacting route and introduce the additive either during compacting or directly into the compounder. The second route was to use the foam forming route and hydrophobize fibres before compounding. The effect of additives was studied using injection-moulded samples containing 20% BSKP fibre in a bio-LDPE matrix that also enabled studying fibre dispersion on a very hydrophobic matrix. The low BSKP fibre amount enabled proper injection moulding when the MFI stayed on a level suitable for the injection moulding process. The additives are presented in Table 2.

| Additive | Manufacturer | Addition method | Amount of fibre, % * |
|---|---|---|---|
| AKD – alkyl ketene dimer | AKD Aquapel A220 | Addition on foam forming | 2 |
| Rosin ester | | Addition on foam forming | 5 |
| Acrylic copolymer | CH-Polymers 1 | Addition on foam formed sheet – spraying | 12 |
| Acrylate copolymer | CH-Polymers 2 | Addition on foam formed sheet – spraying | 12 |
| Si-modified BSKP fibre | Åbo Akademi | Foam forming | 5 |
| Blend of fatty acid derivatives | Struktol TPW 617 | Straight to compounder | 10 |
| Silicone copolymer | Wacker Genioplast PP20A08 | Straight to compounder | 5 |
| Epoxy modified linseed oil | Valtris Specialty Chemicals, Lankroflex L | Mixing of fibre and compacting | 5 |

*Amounts are used according to the manufacturer's suggestion, if there is one

*Table 2. Hydrophobic additives introduced in bio-LDPE-based compounds with 20% BSKP.*

## Results

Figure 21 presents the injection-moulded samples' test bars containing additives added on fibres using both the foam forming and compacting methods. A comparative summary of the mechanical results, MFI and HDT, is presented in Figure 22.

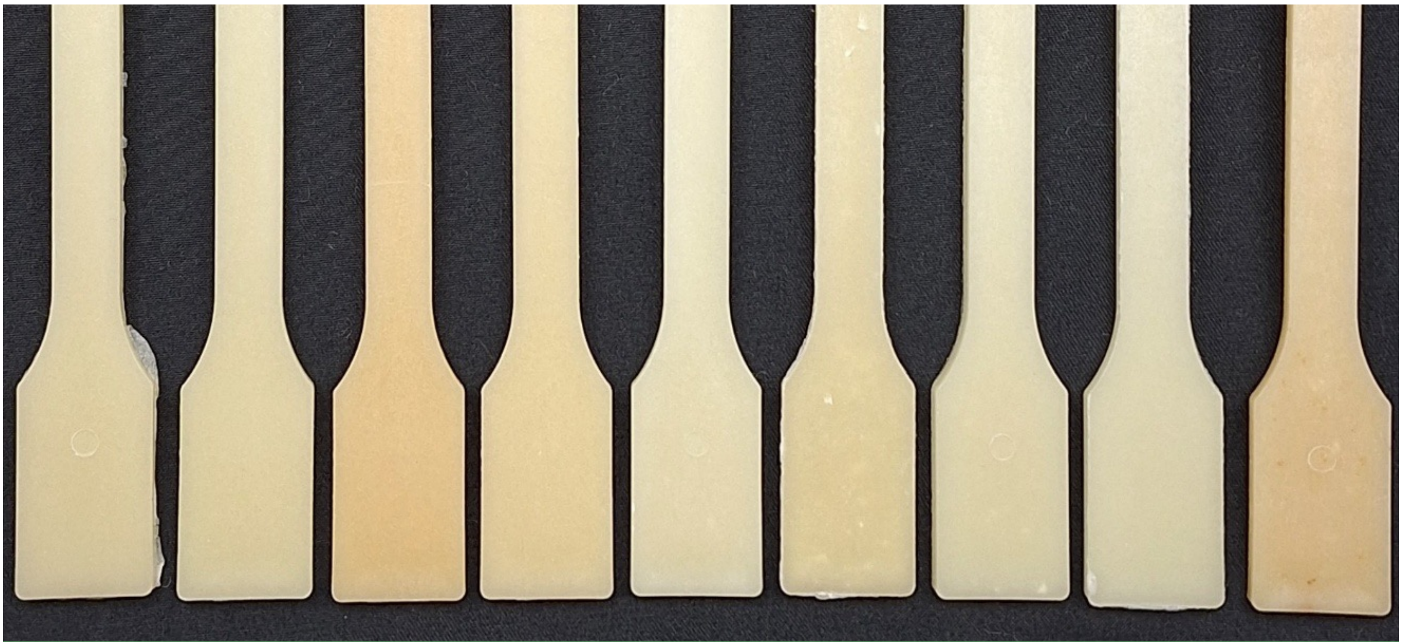


*Figure 21. Injection-moulded samples containing additives for improved fibre dispersion and improved hydrophobic properties. All samples contain 20% of BSKP fibre in bio-LDPE.*

Visually, the best fibre dispersion was obtained using AKD, Si-modified fibre from ÅA, ELO and Rosin ester. Commercial Si-copolymer also provided material with relatively good fibre dispersion and a light colour, meaning low heat stress on the fibre during processing.

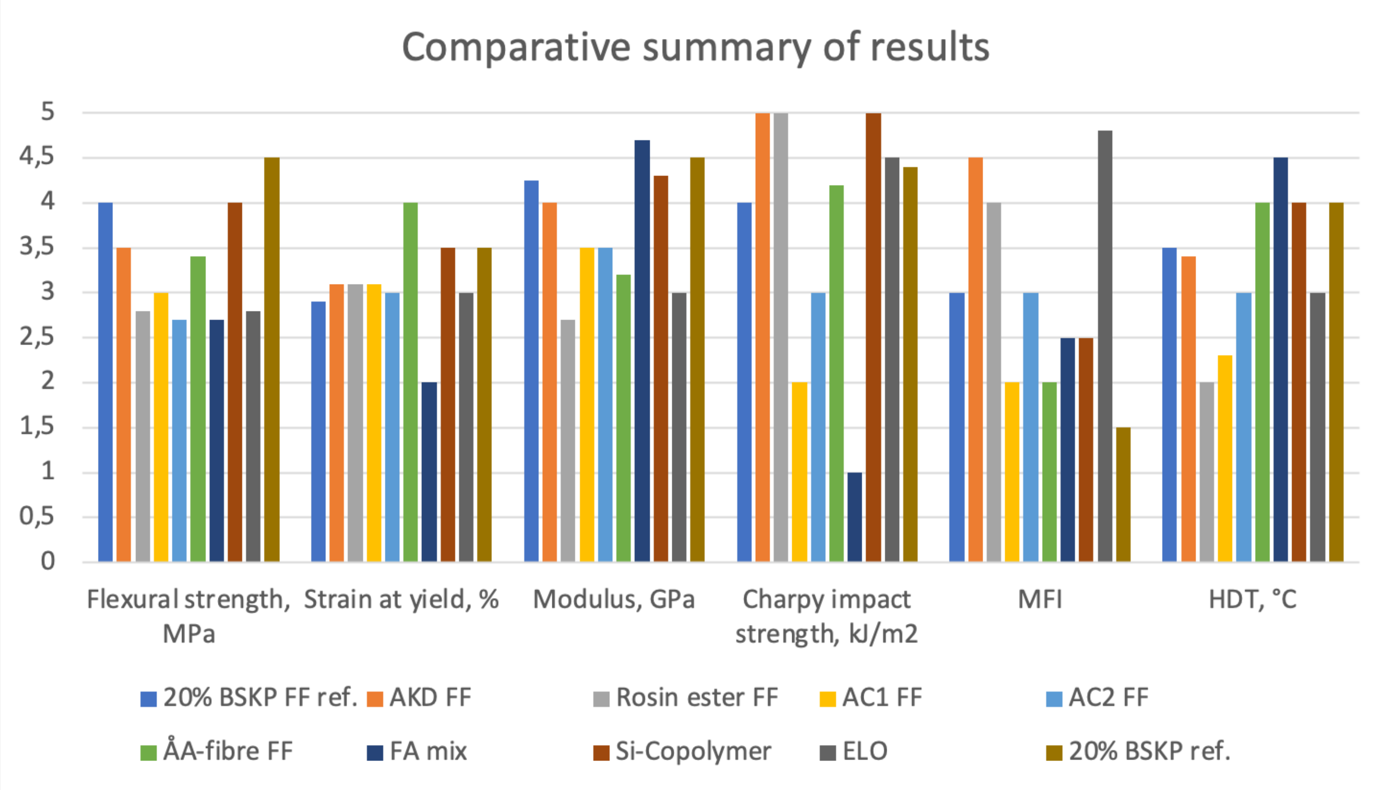


*Figure 22. Comparative summary of mechanical strength, MFI and HDT results, for samples containing hydrophobic additives. Scale 1 to 5, where 5 is the best and 1 is poor value.*

The summary of results other than water absorption is presented in Figure 22 and shows that processability, MFI increase, is most improved with 'greasy' additives ELO, AKD and Rosin ester. In addition, the additives that were added directly into the compounder, FA mix and Si-copolymer, had a positive effect on processability. For mechanical properties, the best positive overall effects were provided by Si-copolymer, AKD and ÅA modified fibre. ELO and Rosin ester were able to provide an increase in the Charpy impact strength without compromising flexural strength properties too much. A slight 3% increase in modulus was gained using FA mix, which probably comes through improved fibre dispersion. The HDT value in general is quite low, 45°C in FF ref and 47°C in compacted bio-LDPE 20% BSKP ref materials. An increase slightly below 3% was found with FA mix additive, and a 5% increase with ÅA modified fibre compared to their references.

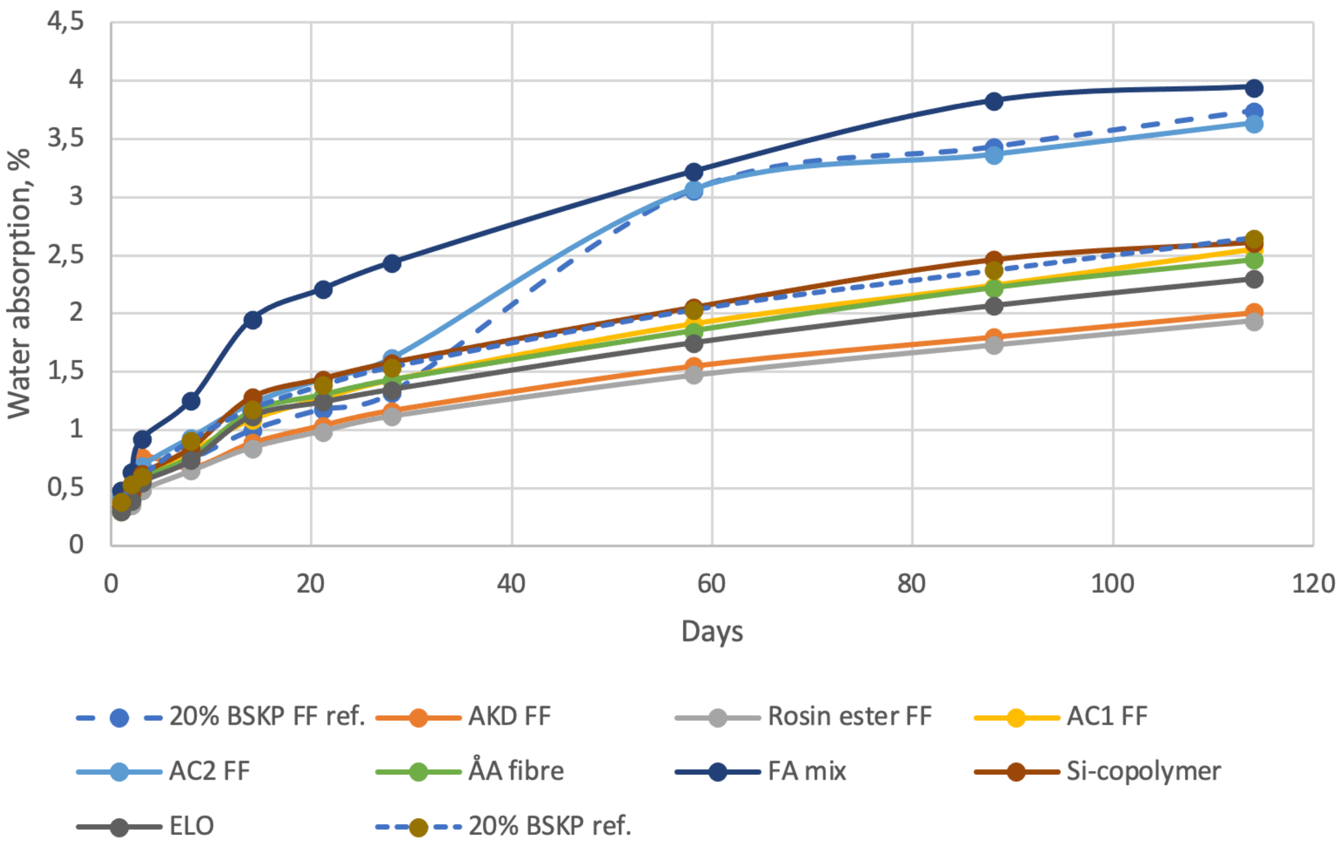


*Figure 23. Water absorption results for injection-moulded bio-LDPE+20% BSKP fibre samples containing hydrophobic additives with a test period over four months.*

Water absorption results over a four-month test period (Figure 23) show clear differences among the samples. Even the reference samples without additives, but with different fibre treatment methods, show different behaviour. The FF treatment may leave some foaming agent, in this case water-sensitive polyvinyl alcohol (PVA) residues, that may have caused the highly increased water absorption in samples FF ref and AC2 FF after one month in water. In other FF samples with hydrophobic additives, the hydrophobic layer may have blocked PVA and provided a significant improvement in water absorption. In particular, AKD and Rosin ester treatments show a 46% and 48% reduction in water absorption, respectively, compared to FF ref., and a 24% and 27% reduction, respectively, compared to compacted 20% BSPK ref. FF-treated ÅA modified fibre also showed 34% and 7% reduced water absorption compared with FF ref and compacted ref materials, respectively. Compacted ELO, which is also covalently bonded with BSKP fibre, showed a 13% reduction compared to a sample without a hydrophobic additive. However, the sample with a typical commercial process and dispersion additive, FA mix, showed increased water absorption properties. Four-month water absorption of injection-moulded neat bio-LDPE was 1.6%, which is only 18% less than that with Rosin ester additive.

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# Biocomposites with a commercial fire retardant (FR) additive

Biocomposites typically contain oil-based polymer matrices such as PP or PE in combination with ligno-cellulosic or natural fibres, which are materials susceptible to burning and keeping the fire going. The most widely used fire retardants for biocomposites are phosphorus containing char-forming additives such as ammonium polyphosphate (APP), water-releasing mineral or inorganic fillers, or heat swellable intumescent flame retardants (IFR) with additive combinations such as APP or melamine polyphosphate (MPP) with a carbon source such as lignin. Mineral fillers such as aluminium trihydrate or magnesium hydroxide are typically needed in very high loadings over 50%, which was too much to be added with other fillers. The multiple additives needed in IFR were not a good choice either. APP has the possibility to provide flame resistance at an addition level of below 30%, so it was selected as a reference for the flame-resistant biocomposite materials and added in an amount of 25 wt% in the 20% fibres (BSKP or sawdust) containing compounds prepared at VTT. Therefore, the total filler amount in compounds was 45%, which is typically near the limit for injection-mouldable thermoplastic ligno-cellulosic fibre-containing compounds.

## Results

The results for commercial FR additives containing injection-moulded PP-Circo and bio-LDPE compounds with 20% BSKP or 20% sawdust are presented in Figures 24 and 25. The results are presented in relative form, compared within each material type, due to the scientific paper being in the preparation process.

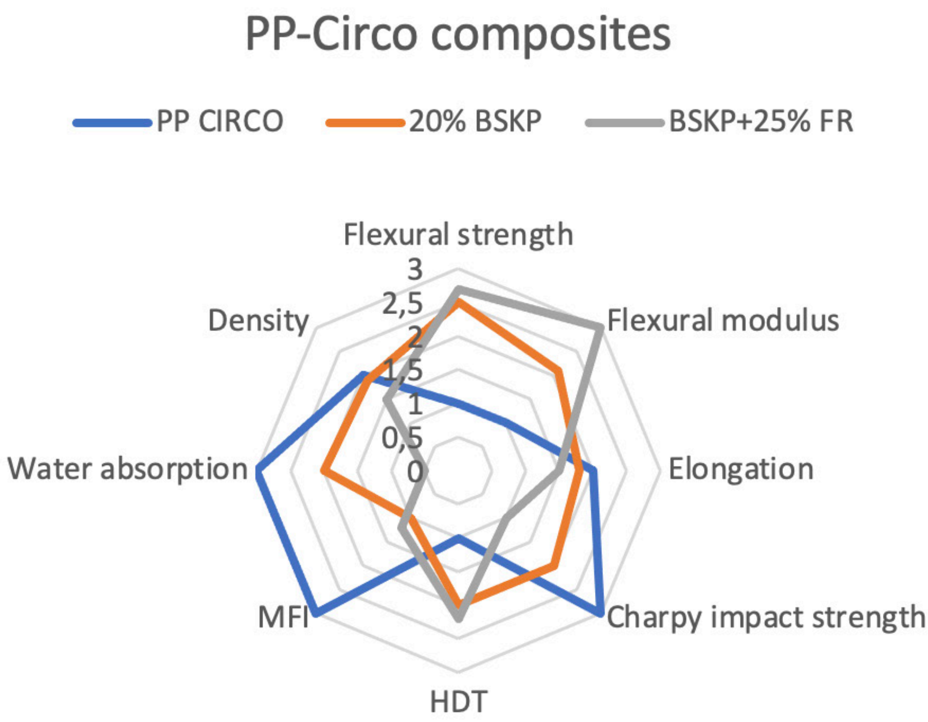
The results in Figure 24 show a reduction in the processability of PP-Circo when wood-based fillers and flame retardants are added to the compound. The MFI of injection-mouldable PP-Circo (MFI of 22 g/10 min (190°C @2,16 kg)) drops to a level below 5 g/10 min with BSKP and below 15 g/10 min with a sawdust-containing composite. An additional 25 wt% of FR did not have a significant effect on MFI, which is positive information from a processing point of view.

Due to the fillers having a higher density than PP-Circo (0.92 g/cm3) the density of the composites increased by a maximum of 20%.

For mechanical properties, both flexural strength and modulus increased with both 20% BSKP and 20% sawdust addition, and even more due to an additional 25% FR addition, providing very stiff materials with flexural modulus >2800 MPa and flexural strength over 50 MPa with BSKP-containing and 40 MPa with sawdust-containing materials with and without FR. At the same time, elongation dropped slightly, and a reduction was also found in Charpy impact strength properties. There was even an 85% reduction in composites with 20% sawdust+25% FR and a 63% reduction in 20% BSKP+25% FR containing composite. This indicates that there is not enough covalent coupling between the polymer matrix and filler to retain impact properties.

For HDT, the fillers had a positive effect by providing a 15 to 20°C increase in the heat deflection temperature with or without FR.

The strongest negative effects of FRs were on the one-month water absorption, which was roughly ten times higher than with neat PP-Circo. The 20% wood-based fillers caused an increase by only 30% compared to 40% with PP-Circo.



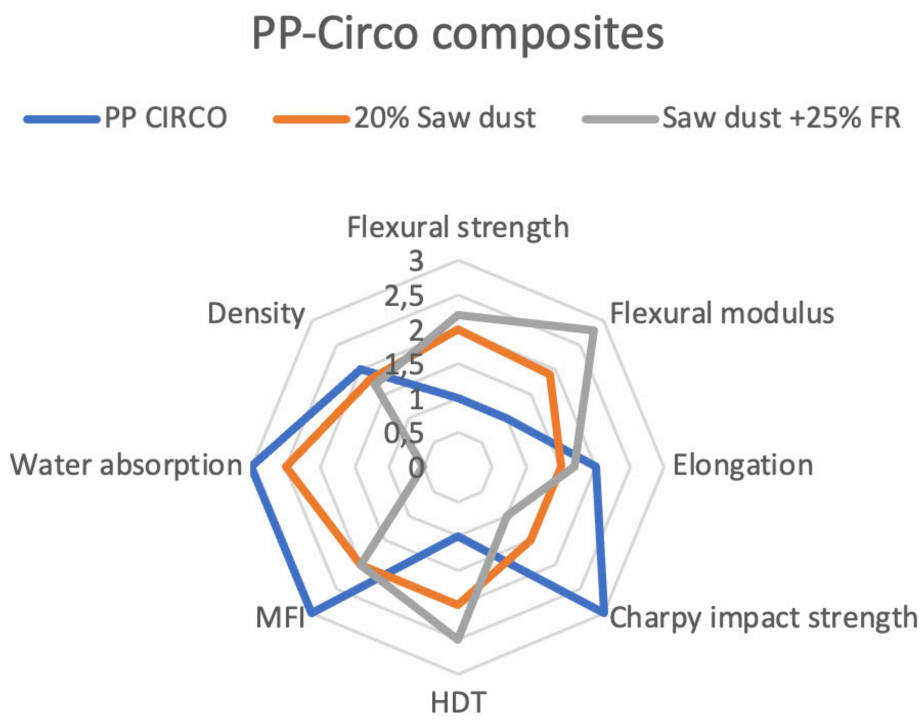




*Figure 24. Relative results for injection-moulded PP-Circo composites with 20% BSKP or 20% sawdust and 25% flame retardant (APP). The scale 1 to 3 represents the following: 1 is a poor or reduced result, 2 is a medium result, and 3 is a good or improved result compared to PP-Circo.*

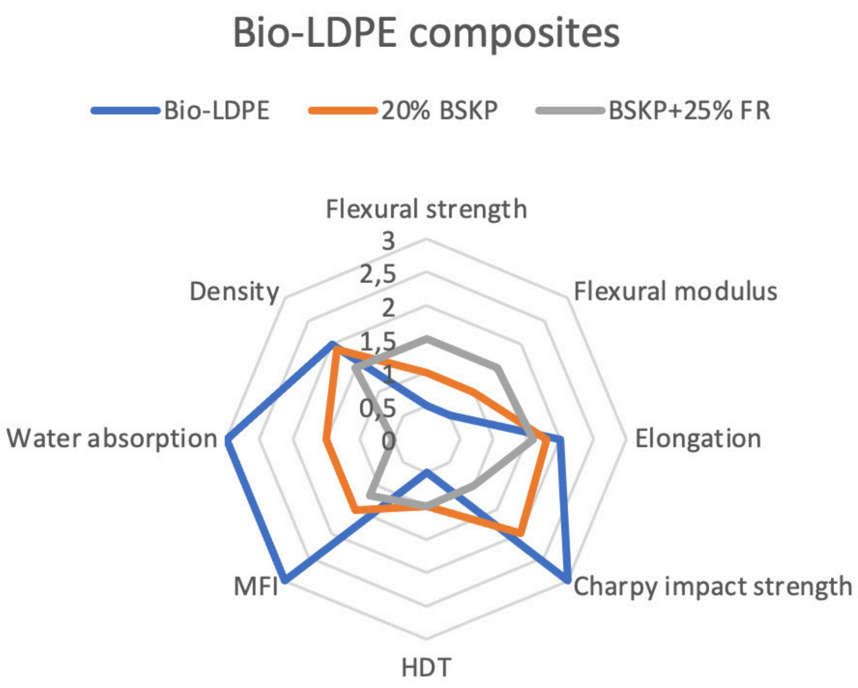
The results in Figure 25 show a significant reduction in processability of bio-LDPE when wood-based fillers and flame retardants are added to the compound. The MFI of injection-mouldable bio-LDPE (MFI of 121 g/10 min (190°C @2,16 kg)) dropped to a level below 5 g/10 min with BSKP and BSKP+FR, and below 15 g/10 min with a sawdust and FR-containing composite.

Due to the fillers having a higher density than PP-Circo (0.917 g/cm3), the density of the prepared composites increased by a maximum of 26%.

Significant changes in mechanical properties were also found for bio-LDPE composites. Flexural strength with 20% BSKP addition was more than a three-fold increase, and it was more than a two-fold increase with 20% sawdust addition, and an extra 20% strength increase due to an additional 25% FR addition. The tensile modulus increase was three- to five-fold in sawdust and BSKP composites, respectively. A 25% FR addition doubled the modulus in sawdust composites and brought a 55% improvement in the BSKP composite, bringing the modulus from very flexible LDPE to the level of typical HDPE, over 800 MPa. At the same time, elongation dropped slightly. A reduction was also found in Charpy impact strength properties. There was even a 75% reduction in composites with 20% sawdust+25% FR and a 55% reduction in 20% BSKP+25% FR containing composite. The mechanical results for bio-LDPE composites indicate that there is not enough covalent coupling between the polymer matrix and filler to retain impact properties.

The original low HDT value, of bio-LDPE, 33°C increased by 4 to 15°C with wood-based fillers and FR, potentially enabling some applications where high temperatures are not needed. The behaviour of bio-LDPE composites in water absorption test was very comparable with PP-Circo composites. The one-month water absorption with FR was over fifty times higher than with neat bio-LDPE. Furthermore, 20% of wood-based fillers caused an increase of only by nine to eleven times compared with bio-LDPE.

The limiting oxygen index (LOI) was analysed in ÅA. The results showed improved LOI results for all prepared FR-containing composites, exceeding the limiting oxygen index of 21 O2-% as it was below 18 O2-% in all PE and PP compounds containing 20% cellulose or sawdust. However, the compounds with only one FR, 25% of APP, showed moderate flammability properties. The total filler content in these compounds was 45%, which is near the limit for injection-mouldable material. So, the result of these FR reference compounds was that a novel flame retardant or mixtures of FRs with synergistic phenomena were needed and studied in greater detail at Åbo Akademi.



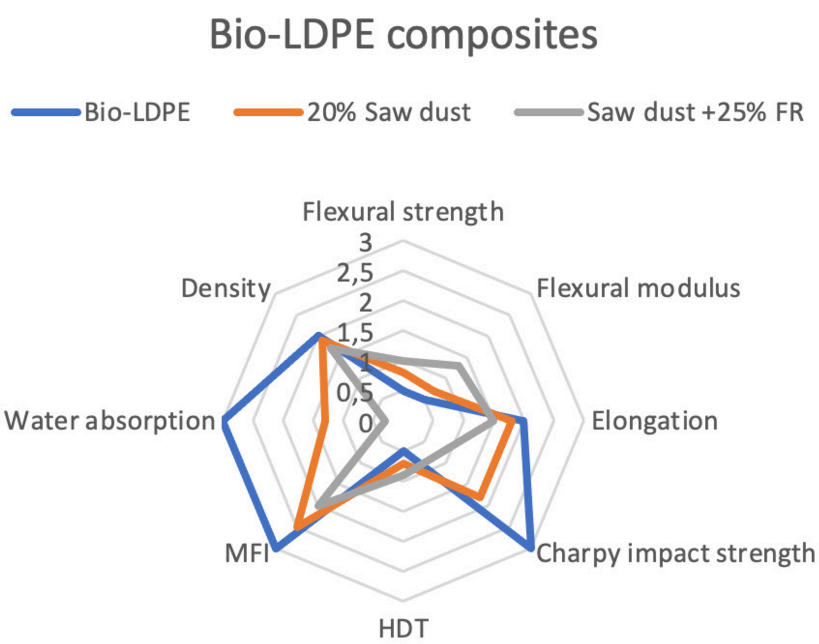




*Figure 25. Relative results for injection-moulded bio-LDPE composites with 20% BSKP or 20% sawdust and 25% flame retardant (APP). The scale 1 to 3 represents the following: 1 is a poor or reduced result, 2 is a medium result, and 3 is a good or improved result compared to bio-LDPE.*

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# Synergistic flame-retardant formulations for cellulose-reinforced polyolefin biocomposites

Biocomposites are increasingly used in applications such as consumer electronics, where improved fire safety is required. Our goal was to identify an effective, commercially available, environmentally friendly flame retardant and to develop formulations that can pass common fire safety tests (UL 94 V0 and the SBI test for building products).

There are several ways to reduce the flammability of polyolefin–cellulose composites. Common approaches include adding mineral fillers, using halogen containing retardants, and using phosphorus or silicon based additives. Mineral fillers usually require high loadings to be effective, which can impair the material's properties, while halogenated retardants are effective but raise environmental and health concerns. For these reasons, phosphorus and silicon based strategies were prioritised. Ammonium polyphosphate (APP) was selected as the primary, more environmentally acceptable flame retardant. The main tasks were to identify optimal compositions to achieve specific fire classifications for the biocomposites, such as UL94 V0 or SBI E, and to minimise flammability by reducing the peak heat release rate (PHRR) in cone calorimetry while maximising the limiting oxygen index (LOI), using the lowest possible amount of flame retardants.

## Results

A series of polypropylene-based biocomposite formulations combining ammonium polyphosphate (APP) with various additives were prepared and evaluated using the limiting oxygen index (LOI) method. In addition to APP, several additives were investigated, including aluminium diethyl phosphinate (DEPAL), melamine polyphosphate (MPP), aluminium hypophosphite (AHP), APP-based intumescent flame retardants, aluminium hydroxide (ATH), hydroxy-terminated polydimethylsiloxane, and various clays and silicas.

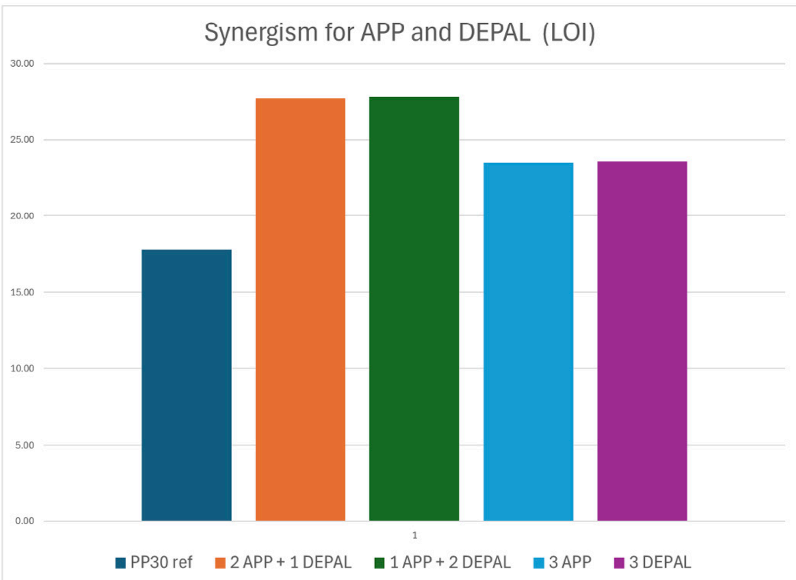


*Figure 26. Synergism in LOI number for APP and DEPAL in the composites with ~30% cellulose*

The most effective formulations contained APP, aluminium diethyl phosphinate (DEPAL), and calcium carbonate (Figure 26). A synergistic effect between APP and DEPAL was observed, while calcium carbonate was found to be necessary to preserve cellulose during melt processing.

It was also observed that flame retardancy (as indicated by LOI) decreased when composites with lower cellulose content were used.

Melamine polyphosphate (MPP) was also evaluated, and it demonstrated flame-retardant performance comparable to APP. It exhibited a similar synergistic effect to DEPAL, yielding slightly higher LOI values at flame-retardant loadings above 30 wt%.

A further synergistic effect was identified upon the addition of hydroxy-terminated polydimethylsiloxane to the APP (or MPP)/DEPAL system. This effect was most pronounced in polyethylene-based composites. LOI data illustrating this behaviour are presented in Figure 27.

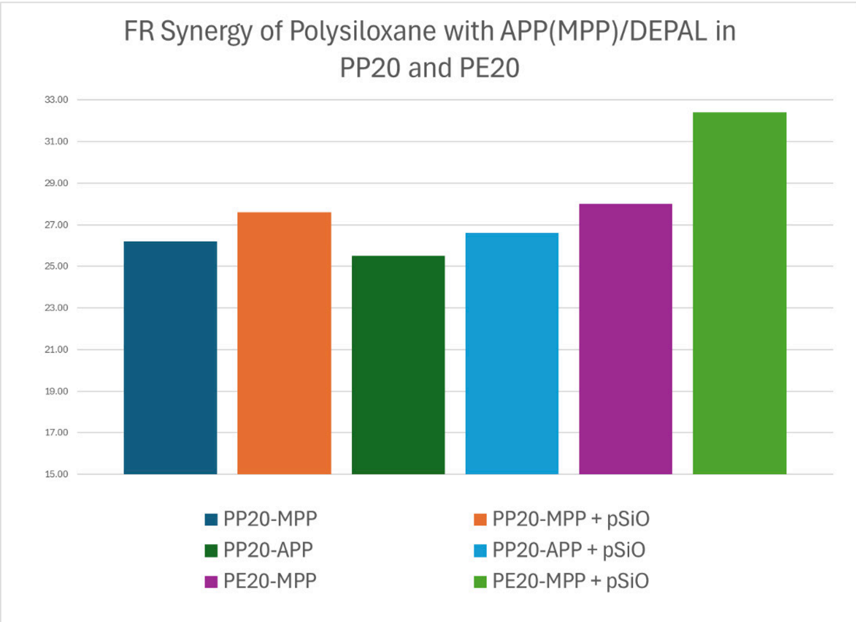


*Figure 27. Synergism in LOI number for APP(MPP)/DEPAL and hydroxy-terminated poly-dimethylsiloxane in PP and PE composites with 20% cellulose*

With these formulations, polypropylene (PP) and low-density polyethylene (LDPE) composites containing 20 wt% cellulose achieved a UL-94 V0 classification with total flame-retardant loadings below 40 wt% (corresponding to 60 wt% total filler content).

Cone calorimetry tests were conducted on multiple composite formulations to evaluate differences in burning behaviour under forced flaming conditions. The addition of 20 wt% cellulose reduced the peak heat release rate (PHRR) by more than twofold in polypropylene and by nearly threefold in polyethylene. A similar trend was observed in flame-retarded composites: at 25 wt% flame-retardant loading, the PHRR was reduced by more than twofold in polypropylene and by nearly threefold in polyethylene. The results are presented in Figure 28.

Further cone calorimetry tests showed that increasing the flame retardant loading (up to 50 wt%) reduced the peak heat release rate (PHRR) to 185 kW/m² and the time to ignition to 40 s, indicating that the material could potentially achieve an E classification in the SBI test. However, such high filler content (65%) may be detrimental to the mechanical properties of the material.

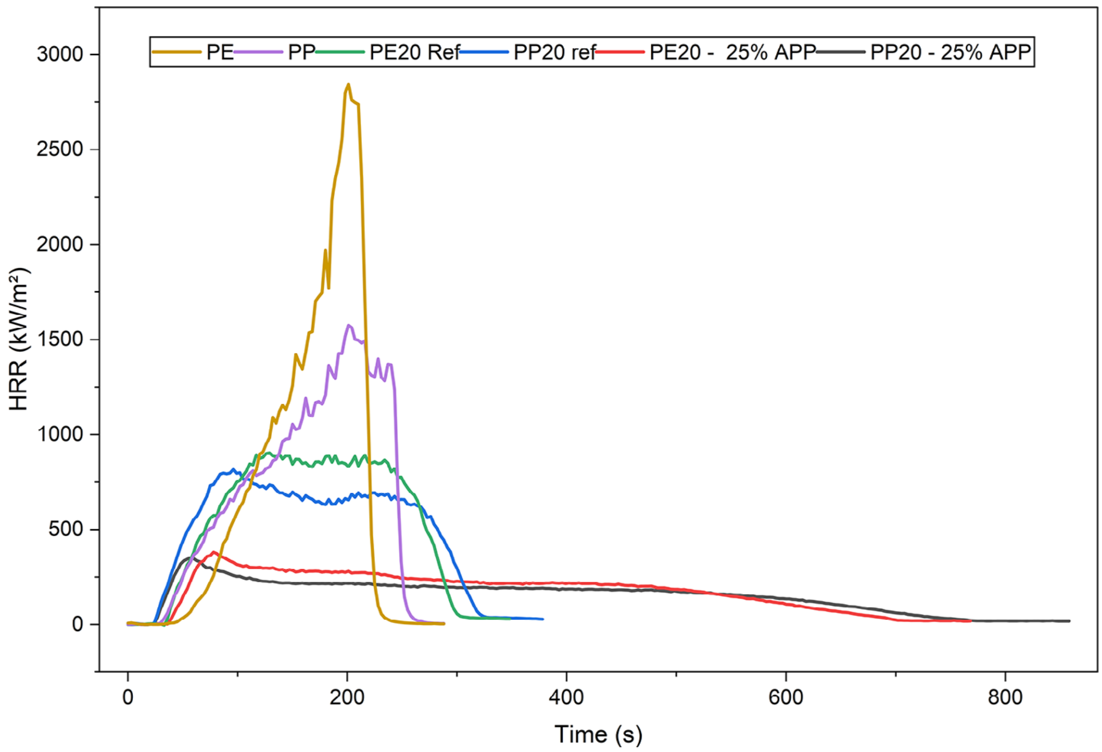


*Figure 28. Heat release rate for the flame-retarded composites, reference composites, and pure polymers in the cone calorimetry analysis.*

In a subsequent step, to preserve mechanical properties, the total flame retardant content in follow-up formulations was limited to 25 wt%; at this loading, LOI values above 22 for PP and above 23.5 for LDPE were obtained.

In conclusion, effective flame retardancy in polypropylene- and polyethylene-based biocomposites was achieved through synergistic combinations of APP or MPP with DEPAL and selected co-additives. Calcium carbonate was essential for stabilising cellulose during processing. Additional improvements were observed with hydroxy-terminated polydimethylsiloxane, particularly in polyethylene systems.

Optimised formulations containing 20 wt% cellulose reached a UL-94 V0 classification at flame-retardant loadings below 40 wt%. Cone calorimetry confirmed significant reductions in peak heat release rate, with both cellulose and flame-retardant additives contributing to improved fire performance. Higher loadings (up to 50 wt%) further reduced PHRR and ignition time, suggesting the potential for an SBI E classification, although at the expense of mechanical properties.

All experimental results have been compiled and are being prepared for publication.

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# Extrusion trials of biocomposite samples

Sixteen different reference biocomposite samples were compounded using a co-rotating twin-screw extruder with gravimetric feeders. The plastic matrices used were recycled polypropene (PP, Circo, NG Nordic Oy) and biobased low-density polyethylene (bio-LDPE, I'm Green™, Braskem). In addition, various additives and aids were used to improve processability, feeding behaviour, and dispersion of the compounded materials. No additives were used to make chemical modifications. Sawdust (supplier Pihla Group Oy) and bleached softwood kraft pulp (BSKP, supplier Metsä Fibre Oy) were used as fillers with 20-50 wt%. Plastic matrices and fillers were dried overnight, and then compounded and granulated for extrusion.

All 16 biocomposites materials were trialled using a single-screw laboratory extruder. A typical melt temperature for PP was 220°C, and for PE it was 190°C. As expected, most of the biocomposite samples showed moderate or even poor surface quality during first extrusion trials using a commonly used nozzle die (left-hand side in Figure 29).

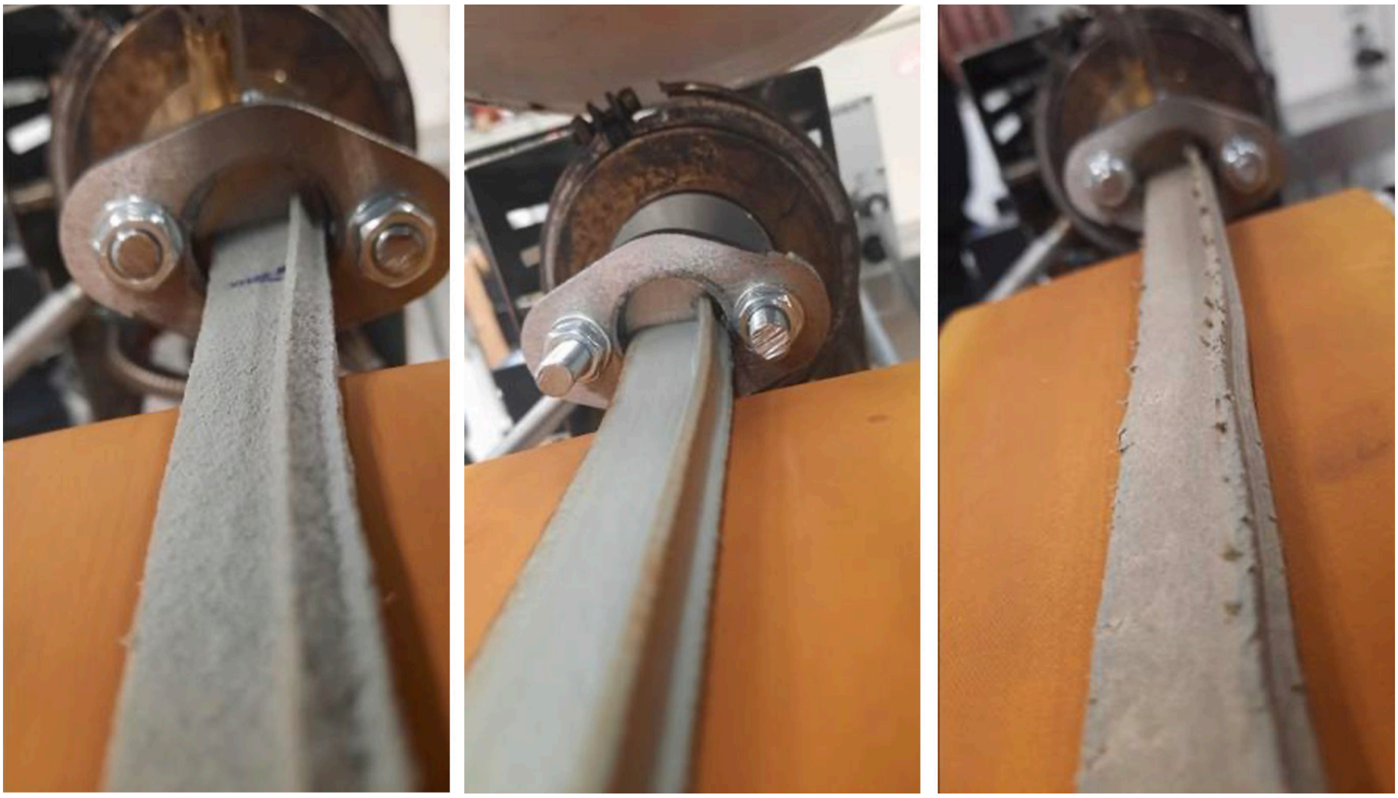

*Figure 29. Variation in the surface quality of biocomposite samples using different extrusion dies and calibration tools. (Images Reijo Heikkinen)*

Several geometries of different extrusion nozzle die and calibration tools were tested, and the surface quality of the biocomposite extrusion profiles was considerably improved (Figures 30 and 31). It was also noticed that when filler content reaches 50 wt% in a biocomposite matrix, melt flow becomes viscous and hence feeding gets very challenging, if not impossible.

*Figure 30. A single-screw laboratory extruder with a T-shape die producing a bio-LDPE with a 20 wt% sawdust biocomposite profile. (Image Kusti Ruokamo)*

*Figure 31. A single-screw laboratory extruder with a flat die producing PE with a 50 wt% sawdust composite profile. (Image Kusti Ruokamo)*

As this was a laboratory-scale trial without an appropriate cooling and profile drawing system, this result can be regarded promising for some bio composite samples for further improvement when scaling up the extrusion process. More attention should be paid to nozzle and die geometries of a bio composite material in question.

The extrusion nozzle was made by stacking plates cut with a laser cutter from 3 mm sheet steel. In this way, the complex internal shapes of the die were formed relatively easily. The plates were welded to each other on the opposite sides. Making a die out of solid steel would have been very difficult with the machine tools available at LAB. In the design of the die, the aim was to consider the flow properties of the polymer. For this reason, various details were made in the die to facilitate the flow. The velocity of the extruded profile must be the same at every point in the die opening so that the profile retains its shape. In this case, the edges of the channel were made more freely flowing by opening the flow restriction.

The converging zone in the die was stepped, but this was not found to cause any problems. In one die prototype, the stepped shape was reduced by grinding, but it did not differ much in the result compared to the stepped shape (Figure 32).

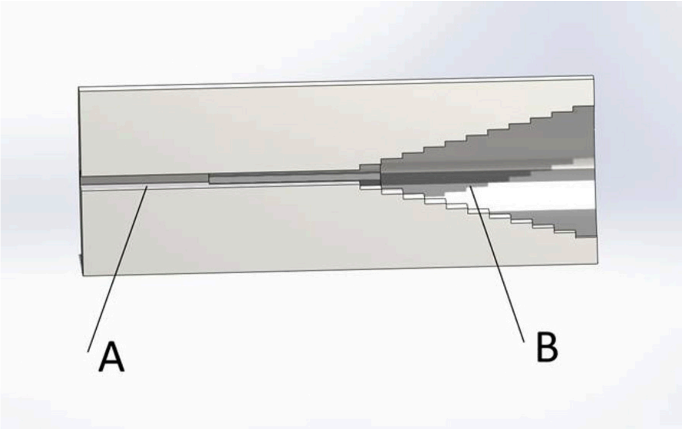


*Figure 32. Vertical section of the die. Converging zone B has steps due to the individual steel plates stacked together. Die land should have a small draft angle to smooth down the surface of the profile. (Image Reijo Heikkinen)*

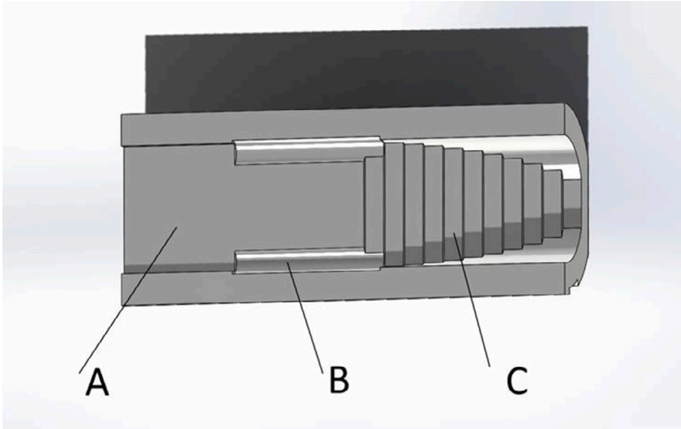


*Figure 33. Vertical section of the die. Land A is parallel to the opposite surface. At the beginning of the die land is shape B, which facilitates flow. Converging zone C will form flow to adapt to the final shape of the profile. (Image Reijo Heikkinen)*

The biggest problem during the test runs was the uneven yield of the extruder. The screw should have been somewhat larger, and the use of a melt pump would have been useful in equalising the yield. With a larger extruder, the plastic could have been pressed against the melt pump, which would have evened out the flow of the plastic.

Calibration was problematic due to the low melt strength of the composite. The profile did not withstand the pulling without breaking. One viable option is to make the land of the die gradually expand at a very gentle angle (Figure 33). This solution would act as a calibration. The length of the die land section should also be long enough, or it should be separate from the rest of the die, which is thermally insulated, in which case it would act as a calibration unit. A longer die would also be useful, as it would increase the pressure in the nozzle. This would improve the solidity of the profile and thus its quality.

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# 3D printing filaments and 3D printing trials for PP and PLA-based biocomposites

## Description

Using 3D printing, it is possible to achieve material savings and create more complex structures for manufactured parts. In addition, reducing material use supports operations in moving towards sustainable development. 3D printing trials were carried out for some PLA and PP-based biocomposites. Before the actual 3D printing, filaments were produced using a single-screw filament extruder. Unfilled commercial PLA filament was used a reference, as it is widely known that it works well in FDM (fused deposition modelling) printers.

## Materials for 3D printing

Four different raw materials with and without 4% Struktol were trialled using a single-screw filament extruder to make filaments of good enough quality for 3D printing.

| | | |
|---|---|---|
| Material 1 | PP with 20% cellulose | 4% Struktol TPW617 |
| Material 2 | PP with 20% sawdust | 4% Struktol TPW617 |
| Material 3 | PLA with 20% sawdust | no additives |
| Material 4 | PP with 20% sawdust | no additives |
| Material 5 | PLA | commercial |

*Table 3. Compounded biocomposites that were produced to make 3D printing filaments.*

All the 3D-printed pieces were produced using the same settings: the nozzle was 0.80 mm, the nozzle temperature was 215°C, print bed temperature was 60°C, and printing thickness was 0.30 mm. Three samples from each material were tested to 3D-print both vertically and horizontally. All the materials except Material 4 were successfully 3D-printed. It can be noted that 3D printing of Material 3, PLA with 20% sawdust, proved to be easy. This is particularly encouraging when considering future development and potential applications.

In addition, non-filled PLA samples were 3D-printed for reference. The PLA-based matrix had been defined as probably the most promising of these biocomposites, so its benchmark was important.

## Results

Biocomposites with a PP matrix seemed to be significantly more sensitive to printing errors and adhered poorly to the substrate, and both ends of horizontally printed samples rose off the substrate when the test piece was no longer straight but bent and was thinner at both ends. The filament of the PP-based biocomposite seemed to break more easily. With PP-based materials, in the event of a printing error, the printed piece wobbled more easily during the final print, especially with samples printed vertically.

PP with 20% cellulose and 4% Struktol (Material 1) was printed for the tensile test with the test samples printed vertically. There were holes in the printing of this material, due to the uneven thickness of the filament. The filament was difficult to make, which is why I couldn't make any more test samples with it. PP with 20% sawdust and 4% Struktol (Material 2) printing was difficult, but in the end it was successful. With this material, there was a temperature deviation in printing, causing the nozzle temperature to drop by about 10-15°C, and the printer displayed an error code. The printer nozzle momentarily lifted from the top of the print, leaving a thread-like thin plastic filament between the piece and the nozzle, and some prints failed because of this. On some occasions, printing could be resumed, and the temperature quickly rose back to the set temperature, and the printing did not fail. When printing vertically, the beginning was better with this material. Little porosity, based on the prints, and smaller nozzle movements seem to suit it better. The filament was partly unevenly thick; these spots were removed, and the printing was successful, so with this material all the test samples could be printed for mechanical tests. Compared to the first material, this was denser, but there was a small margin of error when printing.

The appearance of the printed samples was slightly different for all materials when printing horizontally and vertically, but especially with PP-based biocomposites, post-processing would probably smooth the surface.

PLA with 20% sawdust (Material 3) was significantly more printable, especially vertically. Printing was successful horizontally, as long as the piece to be printed was properly attached to the substrate and remained motionless. If the biocomposite detached from the substrate at the very beginning of 3D printing, this caused the print to accumulate in the nozzle, causing the nozzle to become clogged. This material also solidified much faster, which made it difficult to clean the nozzle if the printed material had time to accumulate in it. With this material, the edges of the prints were smoother; the printed pieces did not wobble during printing, and there was significantly less porosity. The filament of this material also looked much better, uniformly thick, and felt more flexible when bent.

*Figure 34. Test bars 3D-printed from PLA with 20% sawdust in a vertical (left) and horizontal (right) printing direction. (Image Tiina Marttinen)*

Polypropylene tape was used as the printing platform. Especially the polypropylene-based biocomposite adhered to it better, as was expected. When using tape on the printing substrate, it should be considered that the printing does not go over it, and in this case the printing may not stick to the substrate and may even cause a failed printing, and at least cause an uneven quality surface in the printing.

## Tensile test results

Tensile tests were performed for three vertically and three horizontally 3D-printed pieces for Materials 1, 2, 3 and 5. There is a clear difference between the test results based on the direction of the printing (Figure 35), as was expected; horizontally printed pieces are consistently stronger compared to vertically printed pieces.

Variations in the tensile strength results are presented in Table 4.

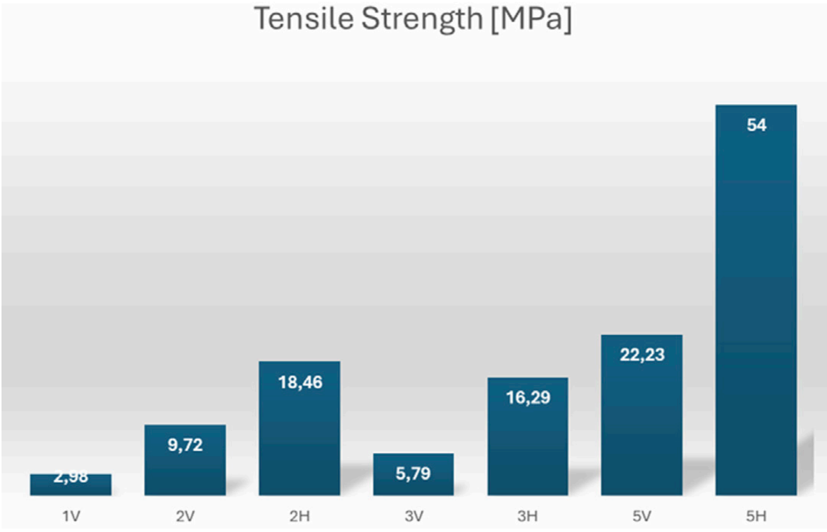


*Figure 35. Tensile strength results of Materials 1, 2, 3 and 5 printed vertically (V) and Materials 2, 3, and 5 printed horizontally (H).*

| Sample | Tensile strength average (lowest-highest), MPa |
|---|---|
| Material 1 (V) | 2,98 (2,056-3,700) |
| Material 2 (V) | 9,72 (9,063-10,418) |
| Material 2 (H) | 18,46 (17,428-19,168) |
| Material 3 (V) | 5,79 (5,385-6,083) |
| Material 3 (H) | 16,23 (15,370-17,670) |
| Material 5 (V) | 22,23 (21,163-24,115) |
| Material 5 (H) | 54,00 (50,525-56,450) |

*Table 4. Tensile strength result variation for Materials 1, 2, 3, and 5. V is vertical, H is horizontal 3D printing direction.*

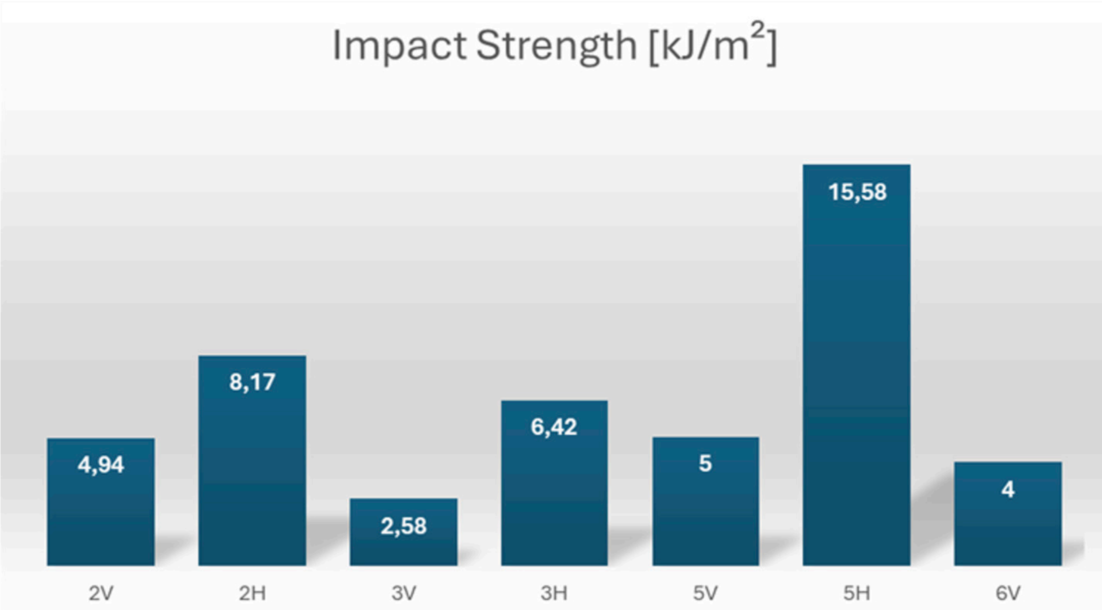


*Figure 36. Test results of the impact strength test for Materials 2, 3, 5, and 6. V is vertically printed; H is horizontally printed.*

## Impact test results

Impact strength tests for horizontally and vertically 3D-printed Materials 2, 3, 5, and 6 were performed, and the averaged results are presented in Figure 36. As can be seen in the results, horizontally printed samples are consistently stronger.

The results of mechanical tests were significantly better in biocomposites when the test piece was printed horizontally. This test result is logical, because the spacing between the print layers is transverse to the test in the impact test. In the tensile test, fracturing is made more difficult by longer fibres. When printed vertically, the adhesion surfaces between the print layers are subjected to stress, and if the adhesion is weaker, the result of the mechanical test is not very good. Based on the test results, porosity seemed to impair the results.

The number of pieces (three) was limited, and these results can be regarded as a starting point for further 3D printability tests.

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## References

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# Foam injection moulding

## Description

Foam injection moulding (FIM) is a method in which a thermoplastic compound is combined with a blowing agent and injected into a mould. This creates lightweight parts with a cellular structure inside. The material is melted and mixed in the injection unit, and the blowing agent (chemical or physical) is spread under pressure. When the mixture enters the mould, the sudden drop in pressure causes gas cells to form and grow in the melt. This creates a typical skin-core structure, with a solid outer layer and a foamed interior. The result is lower material density while keeping the part strong and stable. FIM works with many types of thermoplastic composites, including those with recycled or lignocellulosic fillers. It is commonly used to make parts when reducing weight, saving material, and retaining performance are important. A representative image of a foam injection-moulded sample is presented in Figure 37.

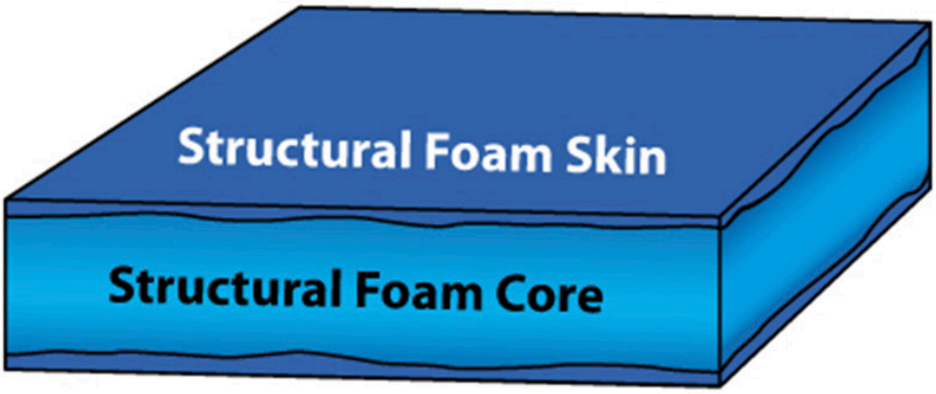


*Figure 37. Representative image of a foam injection-moulding sample*

## Results

Tomographic images of the foam injection-moulded material samples can be seen in Figure 38. The image reveals the foamed core and dense surfaces in the samples, providing a maximum 13% weight reduction with a chemical blowing agent (CBA) and a 17% weight reduction with a physical blowing agent, N2.

The main conclusions from the foam injection-moulding trials are as follows:

- Foam injection-moulding trials showed that the biocomposite formulations developed by VTT can be processed reliably into lightweight components with structural relevance.
- Adding lignocellulosic fillers and bio-based additives helped start the foaming process and led to a clear, well-formed cell structure.
- By adjusting the processing conditions, we achieved stable and mostly uniform foam structures with fewer defects and consistent quality.
- The materials exhibited significant potential for density reduction, contributing to efficient lightweighting without compromising process stability.
- Mechanical performance remained functionally adequate and application-relevant, particularly when assessed.
- The results highlighted how important it is to design the right mix of matrix, filler, and additives to achieve both good foam formation and strong mechanical properties.
- In summary, the study showed that circular, bio-based composite systems are technically possible and relevant for industry, supporting their use in sustainable, high-performance materials.

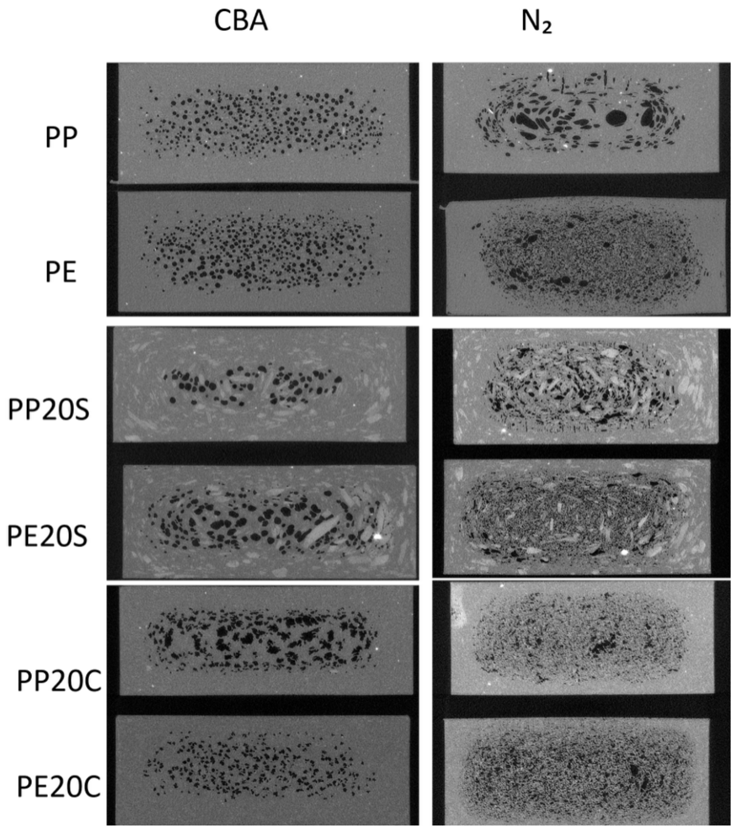


*Figure 38. Tomographic images of PP-Circo, bio-LDPE, PP20S (20% sawdust), PE20S (20% sawdust), PP20C (20% BSKP) and PE20C (20% BSKP) foamed compounds produced with a chemical blowing agent (CBA) and nitrogen (N2)*

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# Long-term properties, safety, and end-of-life

## Summary

Understanding the long-term properties, safety, and end-of-life (EoL) of biocomposites is important for advancing their role as sustainable material solutions. While biocomposites offer clear potential to reduce reliance on fossil-based materials, their environmental performance depends on durability, safety, and viable EoL pathways. Continued development of recycling infrastructure, improved material identification, and expanded knowledge of long-term behaviour and emissions can support their effective integration into industrial applications and regulatory frameworks. At the same time, increasing regulatory attention and growing expectations for circularity and product safety highlight the importance of understanding how biocomposites perform throughout their life cycle, from production to disposal.

Several research tasks therefore aimed to generate knowledge and practical solutions across these dimensions. These focused on the review and analysis of potential EoL options for biocomposites, testing certain material identification methods to support recycling, and evaluating mechanical performance and damage progression using acoustic emission techniques. In parallel, safety aspects such as VOC emissions and biological impacts were investigated to ensure compliance with emerging standards. Finally, the work addressed durability by studying thermal, oxidative and UV stability, and the effectiveness of stabilizers in extending material lifetime and performance.

The results of this research advanced understanding of how biocomposites perform throughout their life cycle. The work identified barriers and opportunities for recycling, demonstrated novel approaches for material identification and performance monitoring, and generated knowledge on long-term stability, damage evolution, emissions, and biological safety. Collectively, these findings provide a stronger foundation for the development, regulation, and wider deployment of biocomposites in sustainable and circular economy applications.

# End-of-life management of biocomposites

## Description

Biocomposites are gaining attention as a more sustainable alternative to plastics, primarily due to their ability to partially replace fossil-based materials with renewable ones. However, their environmental benefits also depend on effective end-of-life (EoL) management. At present in Finland, biocomposite products are predominantly incinerated for energy recovery, while more sustainable EoL options for biocomposites, such as mechanical recycling, lack a systemic collection and recycling solution. This ABiCo research task aimed to map the EoL landscape for biocomposites from a Finnish perspective. It examined where biocomposite waste currently arises based on the application of biocomposite as a material in Finland, and it assessed how these waste streams could integrate into existing waste management and recycling systems. The work further explored potential solutions for recycling, sorting, and collection for biocomposites, drawing on both academic and market insights. Finally, it reviewed the regulatory environment at EU and national levels, considering both current requirements and upcoming legislation that can affect the future of biocomposite EoL.

## Results

Investigation of the Finnish biocomposite market showed that biocomposites in Finland are predominantly made with wood-based fibres, while a matrix can be made from virgin or recycled plastics, including fossil- and bio-based plastics. The application spans a variety of products, from various small consumer products, including cosmetics packaging, kitchen utensils and outdoor tableware, household tools and items, and electronics, to other products such as furniture and interior and construction materials. This results in a number of established waste flows in the existing waste management system that can contain biocomposites: municipal solid waste (MSW), waste electric and electronic equipment (WEEE), bulky waste, construction and demolition waste (CDW), and end-of-life vehicles (ELV). At present, these waste streams do not capture biocomposites for recycling, and the only existing attempts to recycle them were made through take-back systems or take-back pilot projects provided by the producers.

A review of existing research has shown that recycling technologies for biocomposites remain at an early stage compared to those for conventional plastics. Among other possible recycling technologies, mechanical recycling is also often mentioned by producers. Studies on wood-plastic composites (WPCs) confirm that mechanical recycling is technically feasible, with polypropylene-based WPCs retaining over 90% of initial stiffness after three cycles (Burgstaller & Renner, 2023), but broader evidence for post-consumer biocomposite streams is scarce. An important constraint is that natural fibre reinforcement makes composites more sensitive to thermomechanical degradation: repeated processing shortens fibres, resulting in reduced mechanical performance of recycled biocomposites. However, multiple barriers for mechanical recycling arise from the fact that biocomposites are still present in limited volumes and the demand for recycled biocomposite material is unclear. Identification and sorting – a prerequisite for any recycling system – is similarly underdeveloped. NIR spectroscopy can distinguish WPCs of different plastic types (Mauruschat et al., 2016), and hyperspectral imaging has demonstrated 96% classification accuracy for biocomposite samples in a proof-of-concept study (Sormunen et al., 2019), but neither approach has been validated at industrial scale for post-consumer biocomposite waste.

Overall, the analysis shows that establishing a recycling system for biocomposites faces several significant barriers. Biocomposite waste is dispersed across several established waste streams, in which both collection and recycling currently encounter challenges –from yet undeveloped market demand for recycled biocomposite materials to other economic, technological, and infrastructure constraints associated with developing recycling operations. However, internal recycling by biocomposite producers, aided by take-back or buy-back systems, may hold potential for those cases where product return can be arranged and maintained in the long-term. Additionally, the regulatory outlook may drive change for certain product groups in which biocomposites are used. For instance, furniture is identified as a priority group in the EU's first ESPR Working Plan (2025–2030), with a delegated act expected around 2027–2028 that will require information about end-of-life treatment to be available for every product placed on the market, potentially creating the first structural incentives for recycling of biocomposites used in furniture products. A full review and analysis of biocomposite recycling possibilities is being prepared for publication in a scientific journal.

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# Biocomposite identification

## Description

Recycling of wood-plastic composites (WPCs) requires accurate identification and sorting of their constituent materials to ensure sufficient material homogeneity. While optical methods have been shown to distinguish WPCs from pure plastics and identify their polymer types, discrimination between different lignocellulosic fillers inside WPCs has not been previously demonstrated. In particular, no optical method has been reported to distinguish sawdust from bleached softwood kraft pulp (BSKP) within WPCs. This study addresses this research gap by investigating whether attenuated total reflectance Fourier-transform infrared (ATR-FTIR) spectroscopy can identify both the plastic matrix and the wood-based filler in WPCs. Improved identification would support higher-quality recycling of increasingly diverse WPC waste streams.

## Results

WPC samples containing bio-based LDPE and recycled PP with varying amounts of sawdust and BSKP were manufactured and measured using ATR-FTIR from both top and cut cross-sectional surfaces. Spectral data were pre-processed and analysed using partial least squares discriminant analysis (PLS-DA) with leave-one-out cross-validation. Selected spectra are seen in Figure 39. Measurements from the cut surface enabled discrimination between sawdust and BSKP with high accuracy (93.75%) based on lignin-related spectral features. Top-surface measurements showed substantially lower classification accuracy due to migration of wood material away from the surface during manufacturing. The base polymer was reliably identified from both measurement locations. Additionally, a correlation was observed between polyolefin absorbance peak intensity and Young's modulus when measured from the top surface, indicating that ATR-FTIR may also provide indirect mechanical property information.

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## Publications

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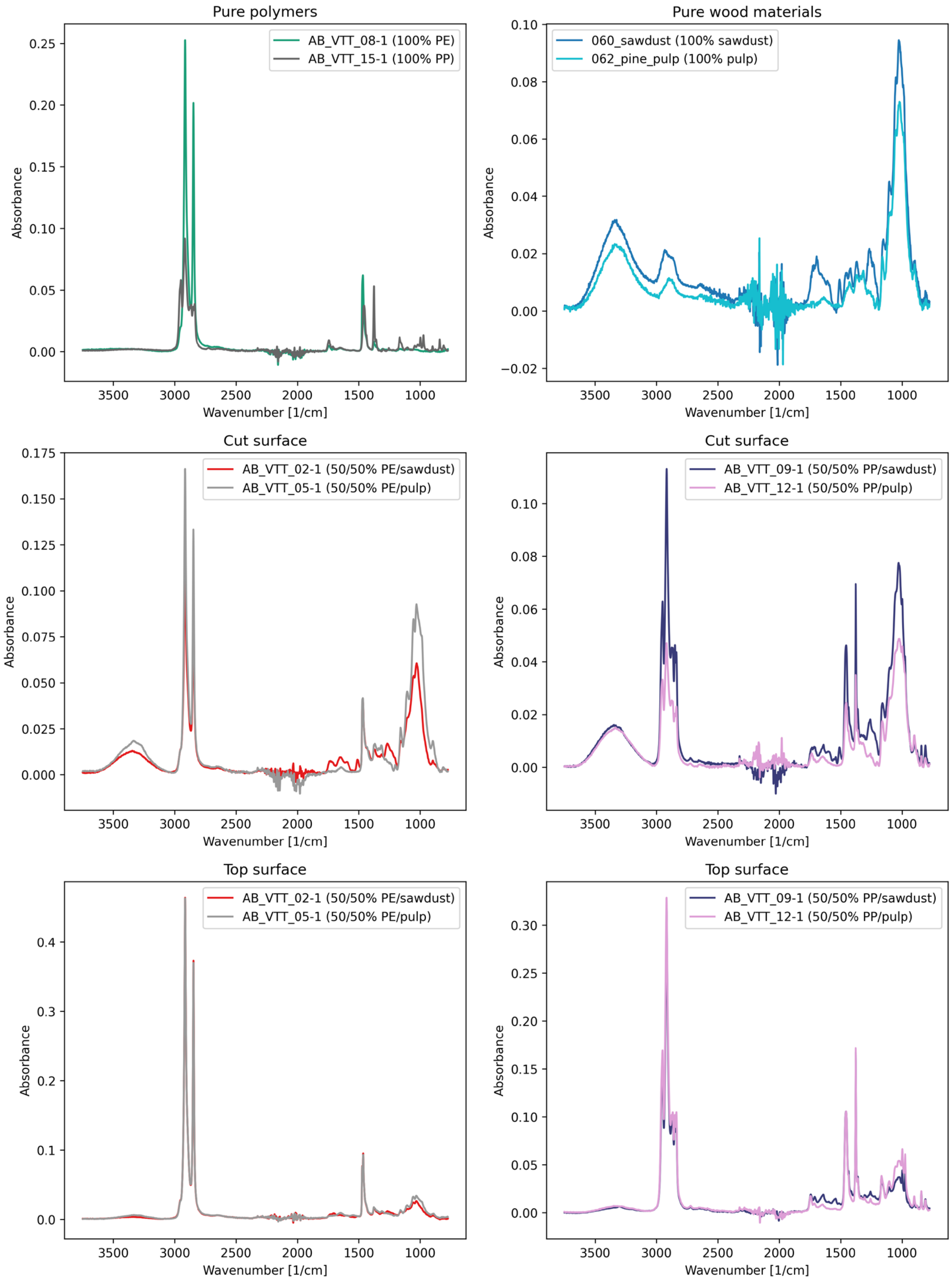



*Figure 39. Representative spectra of the samples: pure base polymers (top left), pure biomaterials (top right), 50/50% PE biocomposite (left) and 50/50% PP biocomposite (right), measured from the cut surface (centre) and top surface (bottom). Note that the noisy region at 1780 – 2750 cm-1 is removed prior to analysis.*

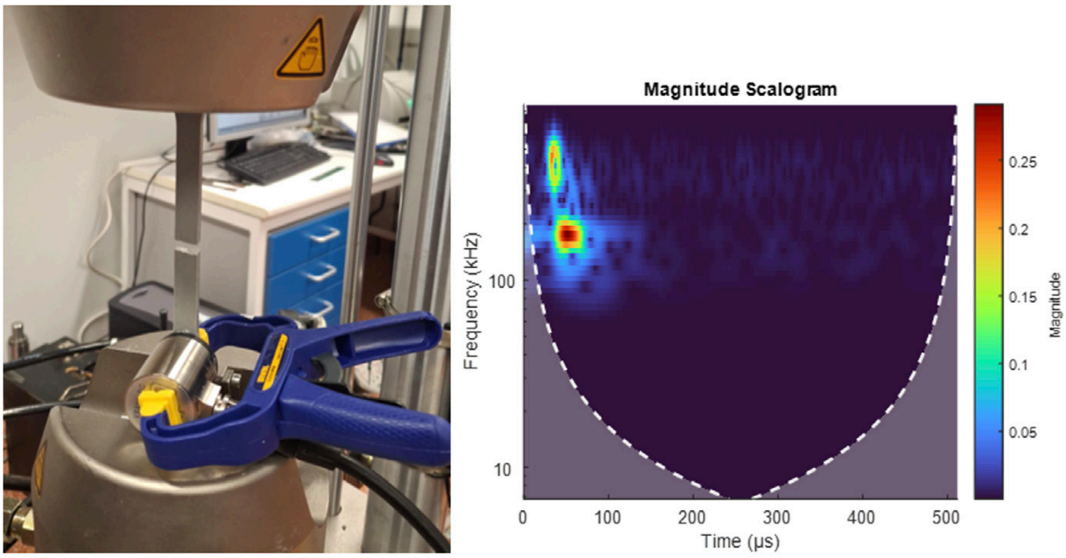
# Acoustic emission testing

## Description

Acoustic emission is one of the most sensitive non-destructive testing (NDT) methods, allowing real-time detection and analysis of damage in materials such as biocomposites. It can be used to detect the initiation of damage and to analyse the progression of damage in real time during mechanical loading. In acoustic emission, no active signal source is used; instead, the acoustic signal is generated within the object itself. Acoustic signals are typically measured in the low ultrasonic frequency range, such as 40 kHz to 500 kHz. When acoustic emissions are measured continuously during the mechanical testing leading eventually to complete failure, they can be used to separate damage modes, including matrix cracking, delamination and fibre breakage. In this project, acoustic emission testing was successfully combined with tensile testing of composite specimens. The acoustic emission data was compared to the stress-strain data collected during the test, and to the ultimate strength and Young's modulus.

## Results

Eleven series of PP and PE -based bio-composites and PP/PE sample-series were studied using AE parallel with tensile strength test. Each series included five parallel dog-bone samples. The bio-composites included sawdust or fibrers 20%/30%. An Instron 8874 was used for standard tensile strength determination. A Vallen VS900-M (sensor with preamp) was used for the AE measurements (Fig. 140a). The AE sensor was connected to the sample using ultrasound gel and a clamp. The frequency range of the sensor is 100-900 kHz. Both wavelet and Fast Fourier Transform (FFT) were used in the analyses. Used machine learning techniques included SOM, extra trees and multivariate regression. By using machine learning and AE data, it was possible to distinguish between different failure modes within the tensile strength testing. According to the literature, damage modes such as matrix cracking, debonding and fibrer breakage may be distinguished from each other using frequency and amplitude analyses (e.g. Prem et al. 2023, Saeedifar and Zarouchas 2020). Wavelet and FFT analyses were used (Figs. 140b, 241 and 342). Besides failure mode analyses, it was possible to estimate the tensile strength using the AE data and machine learning. Both whole test data and early data from a linear phase region were used. The strength estimation was possible for both analyses. Naturally, better estimations were achieved using the whole data. The correlation range was 0.7-0.92.




a) b)

Fig. 40. a) A clamp and ultrasound gel were used to connect the AE sensor to the bio-composite sample during the tensile strength test; b) an example of wavelet signal analysis; two failure modes may be detected simultaneously in different frequencies; PP sample with sawdust 30%.

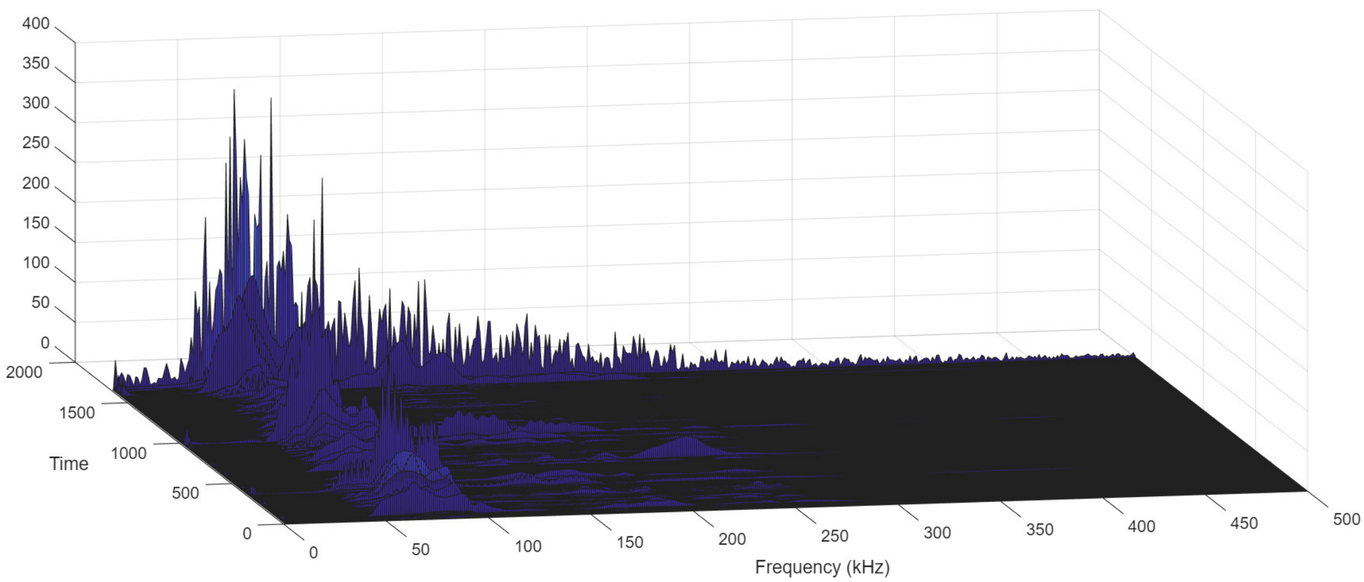



Fig. 41. An example of the measured FFT spectra from AE measurements during a tensile strength test of a PP sample with sawdust 30%. The highest AE signal rate and amplitude occur just before the breakdown.

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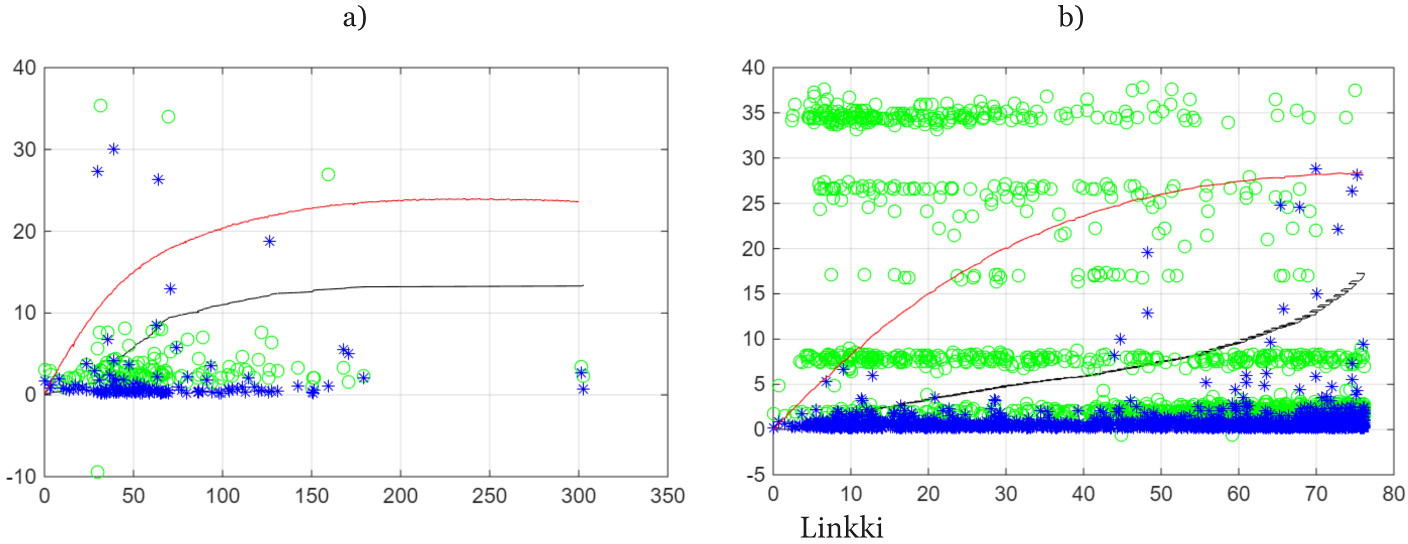


*Fig. 42. Examples of AE responses during the tensile strength test; red – tensile stress; black – cumulative AE events (a.u); blue – AE max amplitude (a.u); green – frequency (a.u); a) Circo – no fibres; b) PP sample with 30% sawdust. The effect of sawdust may be clearly detected by many AE events at high frequencies, indicating debonding and fibre breakage compared to the Circo sample.*

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## Publications

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## Safety testing

### Description

Materials research and development are the most important enablers for addressing the current challenges and opportunities in biocomposites. Product safety standards are tightening, and some limitations to raw material basis might arise, both requiring efforts from the research community. In the research and development of materials, attention must also be paid to addressing the expected future developments in regulation and consumer awareness.

Safety issues in materials and products cover a wide range of properties and testing, such as fire safety, emissions to air, leaching, and migration of biocomposite components in varying conditions, safety of biodegradation products, behaviour in contact with skin or cells or food, and so on (Lestido-Cardama et al]. 2025). In this project, the focused studies of safety testing of biocomposite components included VOC emission measurements of biochars and biocomposites, and microbial and cell testing.

### Results

**VOC emissions**
VOC emissions were evaluated for composites and some components, such as biochar, as shown in Figure 43. Typical emitted compounds are listed in Table 5.

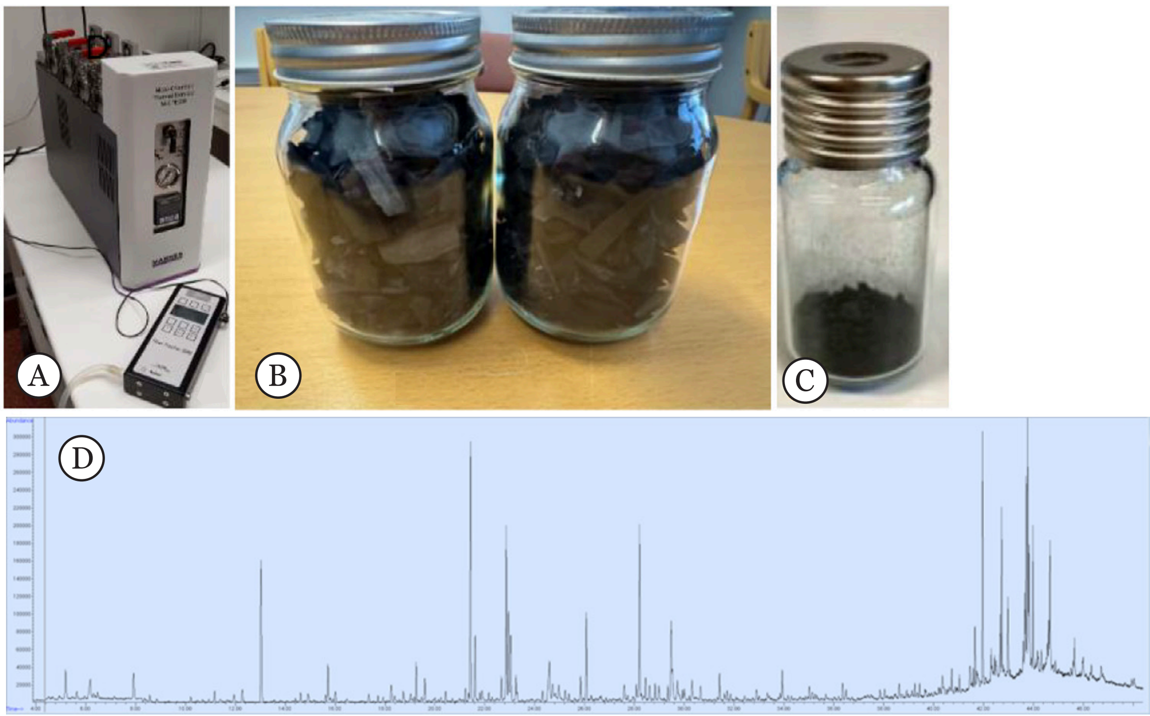


*Fig. 43. VOC emissions measured using a M-CTE250 (µCTE) device (Markes International, Bridgend, UK) with four chambers (A). Biochar samples were collected immediately after processing into closed jars (B) and a 0.5-1.0 g sample was transferred in an air-tight sample tube for emission measurements at 600C, 1400C and 2200C stepwise. An example of mass spectrum of emitted compounds is shown in D. The highest peaks correspond to the most prominent emissions.*

| Compound | CAS |
|---|---|
| Benzene | 000071-43-2 |
| Butanal | 000590-86-3 |
| Butanenitrile | 000109-74-0 |
| Acetamide | 000060-35-5 |
| Benzaldehyde | 000100-52-7 |
| Phenol | 000108-95-2 |
| Phenol, 2-methyl- | 000090-00-6 |
| Phenol, 3-ethyl- | 000620-17-7 |
| p-Cresol | 000106-44-5 |

*Table 5. Emitted and identified compounds in tested biochars.*

The observed compounds are typical chemicals or derivatives used in the production of raw materials or chemicals, or observed in biorefined lignocellulosic materials. Their amounts vary significantly depending on biomass, process conditions, and so on.  For example, phenols and cresols are typical aromatic organic compounds of thermally processed biomass, which can be potentially toxic or mutagenic. Fortunately, the toxic emissions were typically low, and their amounts could be significantly reduced by proper processing means. There is a publication in preparation related to these results.

**Microbial and cell testing**

Antimicrobial polymers and composites are needed, for example, in healthcare, tools, handles, and handrails. Commonly used antimicrobial agents include copper and silver, which have been known for their antimicrobial effectiveness already for centuries. In this project, we tested the possibility of achieving antimicrobial properties using different biophenol mixtures obtained by purifying them from distillates produced by thermochemical processing of birch biomass. Phenols were used in a model system to dope polymeric UV curable resins, which were then 3D-printed to 20 x 20 x 1 mm, 25 x 25 x 1 mm plates, and porous cylinders (diam.=15.3 mm) using a Zortrax Inkspire 2 3D printer (Zortrax, Olzstyn, Poland) (Fig. 44).

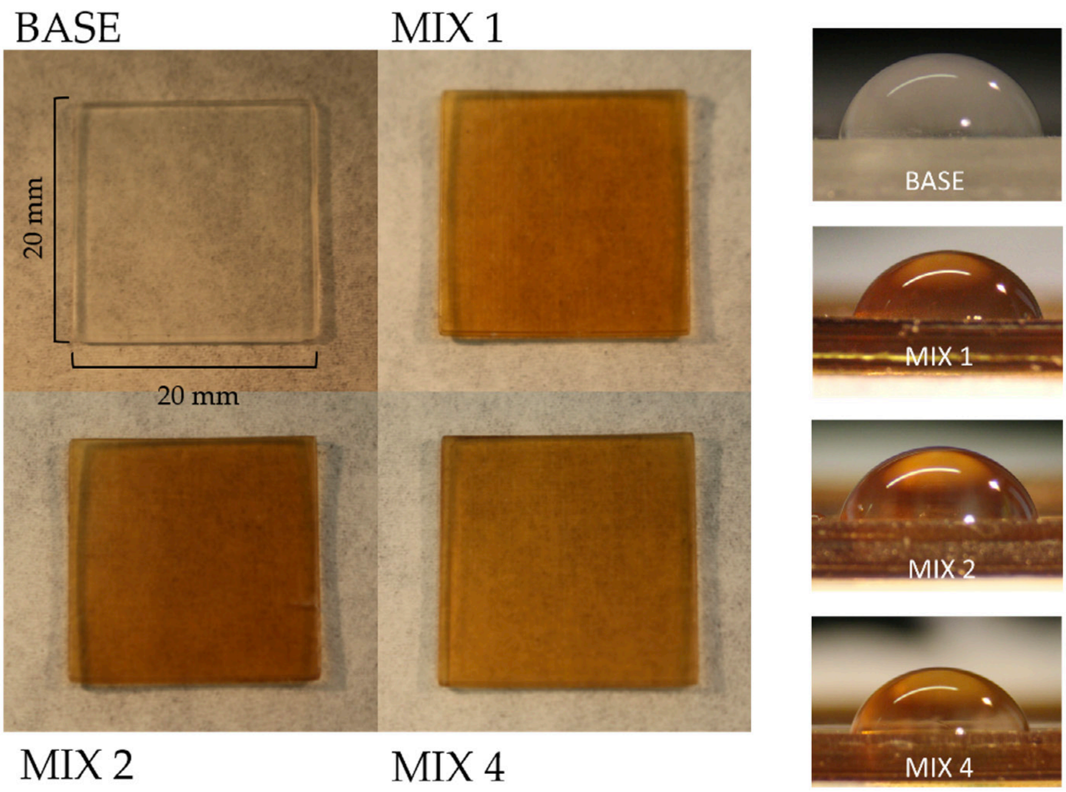


*Fig. 44. 3D-printed test plates of base polymer and doped polymers with different phenolic mixtures. Water contact angle measurement on the right indicated a minor contact angle decrease (from 820 to 720).*

The phenol mixes seemed to improve antioxidative and antibacterial properties against E. coli bacteria, too. Thus, the results indicated the potential of bio-based phenols to modify the surface properties of polymers and provide enhanced performance in functional testing. Further testing is going on.

To gain insight into the skin safety of bio-based coating and composite components, an in vitro human dermal-epidermal co-culture cell model was developed. The cell model (Fig. 45) represents  human skin in 2D, consisting of human BJ fibroblasts and HaCaT keratinocytes. Importantly, the sample exposure is conducted at the air/ liquid interface, thus simulating real-life skin exposure.

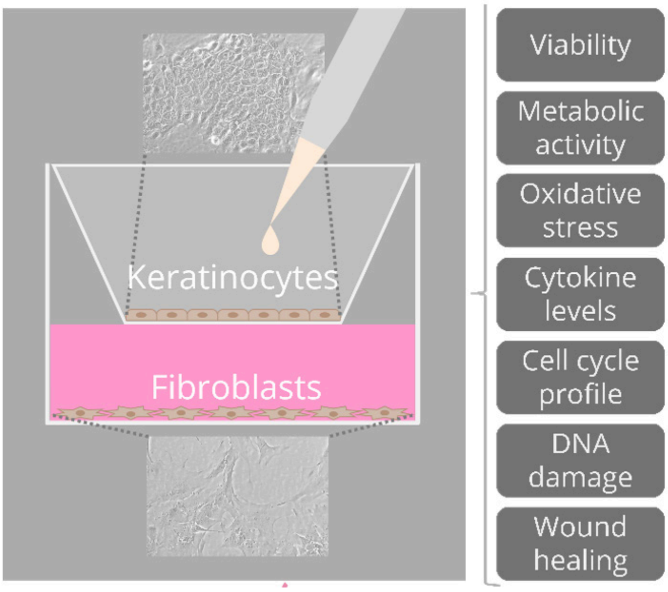


*Fig. 4542.2 A human skin cell model to screen the safety of bio-based materials. Listed are the properties that can be studied with the model.*

The feasibility of the skin model was tested using selected birch, hemp, and spruce slow pyrolysis distillates as exposure samples. The viability, metabolic activity, oxidative stress, cytokine levels, cell cycle profile, and wound healing activity of the harvested cells were measured. The results indicated that the cell model is suitable for sample screening, supported by microbial and compositional analyses. The distillates did not cause major safety concerns at the lowest concentrations, while higher concentrations induced borderline antimicrobial activity but caused adverse effects in the cells. When the skin model was exposed to birch and hemp biochar, especially the hemp char decreased keratinocyte viability and metabolic activity.

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# Thermal and UV stability of biocomposites

## Description

Durability of materials is directly linked to their thermal stability, and UV stability constitutes a major part of weather resistance. Therefore, both thermal and UV stability are key performance requirements for modern materials. In this context, it is necessary to develop stabilized formulations for biocomposites, including both thermal and UV stabilizers.

Well performing stabilized compositions have been reported for pure polymers; however, the same stabilizers can behave very differently in composite systems. For this reason, two thermal stabilizers (Irganox 1010 and Songxtend 2124) and two UV stabilizers (Sabostab UV 40 and Songsorb 9440SB) were incorporated at two different concentrations into cellulose/PP-Circo biocomposites with 20% cellulose content.

The compositions were evaluated by accelerated thermal ageing according to EN ISO 4577:2019, combined with DSC oxidation induction time (OIT) measurements according to ISO 11357 6, to assess the stability of the aged samples. The samples were subjected to thermal ageing at 150°C for 60 days. At selected time intervals, aged specimens were analysed using DSC OIT at 210°C to determine whether sufficient thermal stabilizer remained. An OIT value greater than 10 minutes was considered significant. The results are presented in Figure 46.

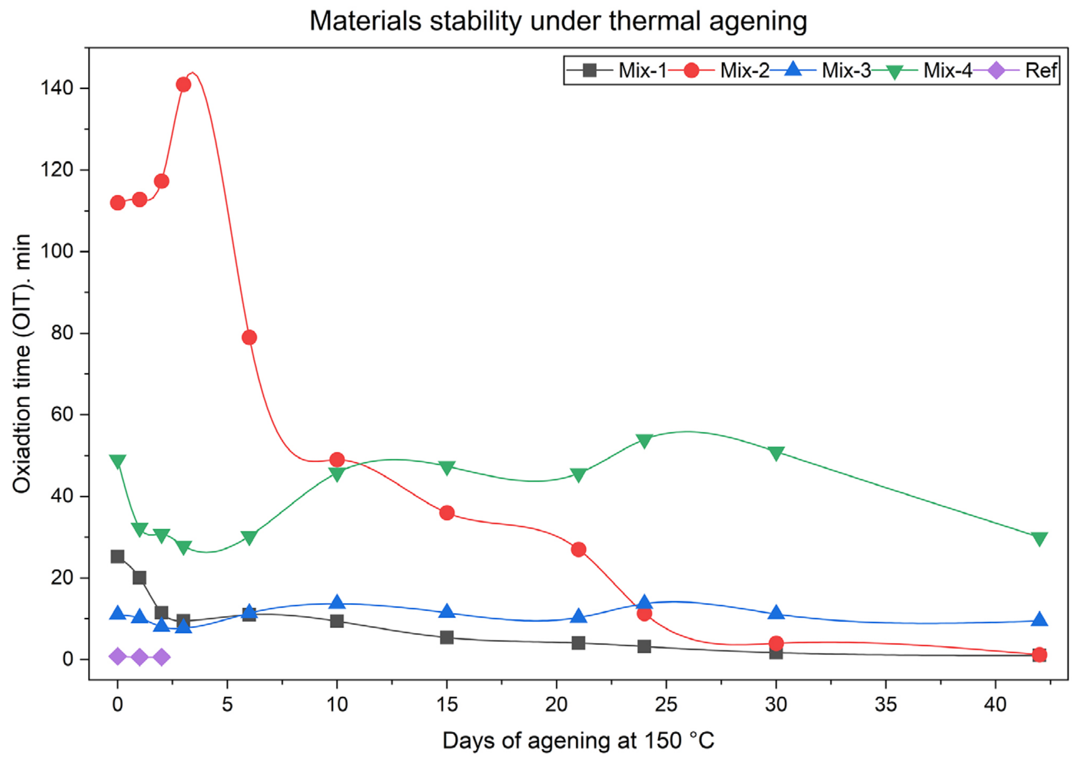


*Figure 46. Thermal stability evaluation for two concentrations of two stabilizers.*

**The determined times during which the stabilizer content remained effective were as follows:**

- Mix-1: 0.2 % Irganox 1010 – 10 days
- Mix-2: 0.4 % Irganox 1010 – 24 days
- Mix-3: 0.16 % Songxtend 2124 – over 30 days
- Mix-4: 0.32 % Songxtend 2124 – over 60 days

Applying the Arrhenius equation, the 60 day ageing treatment at 150°C corresponds to an estimated service life of the material at room temperature of over 50 years.

It is noteworthy that pure polypropylene containing 0.2 % Irganox 1010 did not undergo oxidation during thermal aging over 24 days (OIT over 60 min.), highlighting the distinct behaviour of the composites compared to the unfilled polymer.

UV stability was evaluated using an Atlas Xenotest instrument in accordance with EN ISO 4892 2:2013, employing alternating cycles of UV radiation and water spray for a total exposure duration of 500 hours.

**The following sample sets were evaluated:**

- Three samples from a prior thermal agening experiment: a flame-retarded reference formulation (without UV stabilizer) and two flame-retarded formulations containing 0,1 and 0,2 % of the UV stabilizer Sabostab UV 40, respectively.
- Four polypropylene (PP-Circo) biocomposite samples: 20% sawdust/PP-Circo and 20% cellulose/PP-Circo, each evaluated with and without the addition of 0,1 % Songsorb 9440SB.
- Following exposure, the specimens were characterized via visual inspection, Fourier-transform infrared (FTIR) spectroscopy, and tensile testing.

All unstabilized reference samples exhibited severe degradation, becoming highly brittle, with the UV-exposed surfaces crumbling to a depth of approximately 0.5 mm. Similarly, the formulations stabilized with Sabostab UV-40 showed significant degradation at both concentrations.

In contrast, both formulations stabilized with Songsorb 9440SB exhibited no significant polymeric degradation or loss in tensile strength. The sawdust-containing composite stabilized with Songsorb 9440SB displayed slight surface bleaching compared to the unexposed control; however, this discoloration was attributed to water-induced swelling and the degradation of large wood particles localized at the material surface rather than matrix degradation.

In conclusion, these evaluation protocols successfully identified the most effective thermal and UV stabilization systems, enabling the formulation of optimized stabilization recipes to enhance the long-term durability of these composite materials.

The obtained results are being prepared for publication in a scientific journal.

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# Fatigue testing of composites

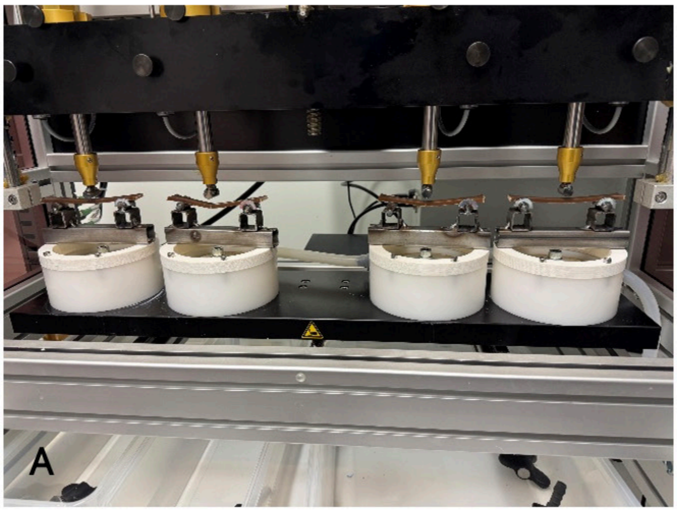
## Description

Fatigue testing (cyclic loading for a large number of cycles) is one of the most important tests to reveal how material defects may lead to complete failure at a stress level far below material's static yield strength. Some materials are particularly prone to fatigue failure, such as aluminium, certain polymers, and fibre-reinforced plastics (V. Kumar 2024).

## Results

For fatigue testing, two PE-based reference composites were selected, as well as the same materials with biochar or wood distillate doping. Fatigue bending testing was carried out using standard samples (4 mm x 10 mm x 100 mm) in an SD Mechatronik CS-4 dental chewing simulator (Feldkirchen-Westerham, Germany) by flexing the samples up to 10 mm in the middle for 50,000 cycles (Fig. 47A). As indicated in Figure 47B, in the reference sets 2-4/4 samples failed before 50,000 cycles. On the other hand, in the best modified set, none of the samples failed.

Based on the results, proper doping of biocomposites with biochar or wood distillates may significantly improve the fatigue properties of biocomposites in addition to other beneficial effects. Further testing is ongoing to gain more data. Similar improvements were observed for these samples with impact testing, too.



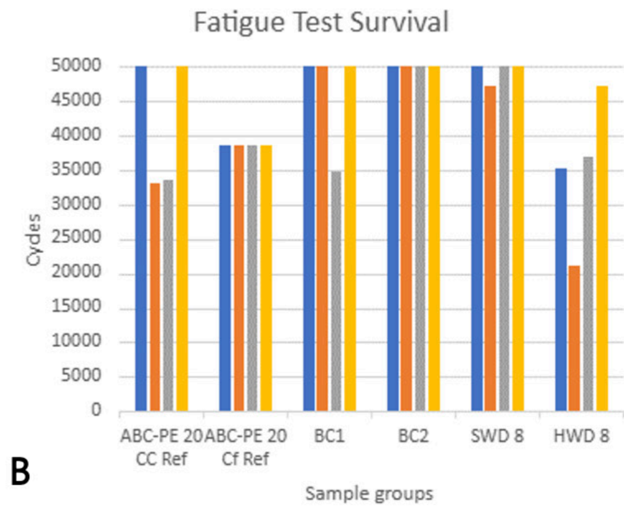




*Fig. 47. A dental bending test simulator (A) was used to determine the survival of four identical samples in each group (B).*

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## References

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## Summary


The research on regulation, biocomposite meta-analysis, and techno-economic assessment within the ABiCo project was conducted to support the development, evaluation and future industrial adoption of advanced biocomposite products. The work focused on understanding how evolving EU and national policy frameworks, material and processing conditions, circularity requirements, and techno-economic factors influence the feasibility and market uptake of biocomposites. The versatile assessment and research strengthened the knowledge base for selecting promising biocomposite applications and for guiding future product development towards technically feasible, economically realistic, circular solutions.

The main objective was to identify the conditions under which biocomposites can move from laboratory-scale material development towards credible industrial implementation. The regulatory work examined current and emerging EU and Finnish policy instruments affecting biocomposite production, use, end-of-life management and recycling, with particular attention to the automotive, construction and electronics sectors. The review showed that biocomposites are influenced by several overlapping regulatory frameworks, including ecodesign, waste, product safety, chemical safety, recyclability, labelling and digital product passport requirements – depending on the product sector and the product. Overall, the regulatory direction is to make circularity and resource efficiency the baseline, and the research shows that material or product labels, secondary markets and harmonised classifications are needed to do create the pull for circular and bio-based materials.

At the same time, the meta-analysis brought together findings from different ABiCo work packages to identify the most promising so-called honeypot applications for biocomposites. The analysis indicated that strong future opportunities are likely to be found in non-load-bearing construction products, furniture and interior products, packaging, selected automotive components and non-structural consumer electronics, where material requirements, processing routes and circularity solutions can be aligned with realistic industrial conditions.

The techno-economic assessment work further translated the technical findings of ABiCo into a decision-support perspective for future commercialization. The synthesis concluded that the studied material concepts are technically feasible at laboratory and early demonstration level, but that full industrial feasibility still depends on application-specific validation, scale-up trials, durability testing, production-rate assumptions and cost modelling. Literature review and market benchmarking confirmed that biocomposite adoption cannot be assessed through material price or single performance properties alone, but requires integrated evaluation of raw material availability, feedstock variability, fibre treatment, compounding, additive formulation, processability, product geometry, quality control, lifetime performance, recyclability and benchmark alternatives. Overall, the project delivered a structured understanding of the regulatory, technical, circularity and techno-economic conditions shaping the future use of biocomposites. The results provide a strong foundation for follow-up development by highlighting promising application areas, key adoption bottlenecks, and the need for transparent scenario-based tools that connect formulation, processing, product performance, life-cycle impacts, circular end-of-life routes and business logic.

# Regulation

An info package related to the latest EU or national policy instruments may have an impact on biocomposite production, use or recycling.

## Description

The Finnish biocomposite sector holds significant potential for growth, supported by the strong Finnish forestry industry, and wood-fibre and cellulose-based solutions. However, regulatory frameworks are essential to ensure that new materials are safe and sustainable. Key regulatory incentives from the EU and national policies are recyclability requirements, proper waste management, and controlled end-of-life behaviour. Biocomposites, however, present regulatory complexity. As hybrid materials combining bio-based components, fossil-based plastics, and various additives, which are being applied across diverse sectors such as packaging, automotive, and electronics, they fall under multiple overlapping regulatory frameworks. Such examples include the plastic packaging requirements, REACH and related regulation for substances of concern, the waste framework directive, and eco-design principles and the digital product passport for improved traceability for priority sectors. For the specific sectors, the focus needs to be on the general changes in the sector, unspecific to the product materials. Consequently, the biocomposite sector is still in the process of defining its role within an evolving policy landscape driven by increasingly stringent recyclability and circularity targets. Without robust traceability, harmonised classification, and clear labelling systems, biocomposites remain among the more challenging material flows to manage, sort, and valorise within current waste management and recycling systems.

## Results

The objective of the regulatory research was to understand how EU and Finnish legislation may affect biocomposite production, use, end-of-life management and recycling. Firstly, the work focused on product-related regulation for the automotive, construction and electronics sectors from the circularity and end-of-life perspective, but it also considered other general legislation steering any decisions in the EU. Secondly, chemical safety and upcoming restrictions have been considered, but as the components are often complex and the listing would require incredible attention to detail, the results are presented as an overview with general risks identified. What has been considered, are the components relevant for ABiCo demonstrators: lignocellulosic fibres, thermoplastic polymers such as PP, PE, recycled PE, recycled PP and PLA, and a range of additives including flame retardants, plasticisers, compatibilisers, hydrophobisation agents, and phenolic fractions. Attention has been paid to potentially sensitive additives and chemicals, such as ammonium polyphosphate (APP), diethylphosphinate aluminium salt (DEPAL), melamine phosphate, maleic anhydride, and selected phenolic compounds.

As a result, the work considers the practical implications, such as product labelling and waste management requirements, that could promote the use, reuse and recycling of biocomposites in the future. The purpose of the component review was to understand possible future restrictions and potential barriers for future scaling of ABiCo solutions. The review of current and future regulatory incentives for biocomposites in the automotive industry, construction and the electronics sector are presented in Figure 48. The European Green Deal, published in 2019, is the over-arching strategy, aiming to make Europe climate neutral by 2050. As one of its key building blocks, the Circular Economy Action Plan (CEAP) was adopted in 2020 to define the initiatives and actions to make sustainable products the norm in the EU and to focus on the sectors where resource use is high and so is the potential for circularity. These sectors include, for example, electronics, packaging, plastics, textiles and construction. The CEAP includes many action points that can be relevant to biocomposites, such as

*Legislative and non-legislative measures establishing a new "right to repair", the Circular Electronics Initiative, a common charger solution, and reward systems to return old devices or the Strategy for a Sustainable Built Environment*. While many of the actions are sector-specific, actions such as *Revision of REACH* or the adoption of the *Policy framework for bio-based plastics and biodegradable or compostable plastics* play an important role in the biocomposite sector.

The regulation responsible for sustainable products as the norm in the future is the Ecodesign for Sustainable Products Regulation (ESPR, Regulation (EU) 2024/1781), which entered into force in 2024. The first ESPR Working Plan for 2025–2030 prioritises textiles and apparel, furniture, tyres, mattresses, iron and steel, aluminium, as well as horizontal requirements related to repairability and recycled content in electrical and electronic equipment. These developments are particularly relevant to biocomposites used in furniture, electronics and other durable products. The ESPR introduced digital product passports (DPPs) as a key tool for achieving its goals; DPPs should enable the tracing of the product component information across the value chain and throughout the life cycle. Depending on the product group, future requirements may concern aspects such as durability, repairability, resource efficiency, recycled content, recyclability and substances of concern. In theory, DPPs should enable efficient sorting and recycling of products. However, the lack of examples and standards for recycling of biocomposites, as well as the complexity of the products, sets limitations on what to do with the information carried in the digital tool.

The ESPR also presented sector-cutting principles for ecodesign, including aspects such as energy efficiency, elimination of hazardous substances, repairability and maintenance, and reduced resource use. Reduced resource use is a key element in the Finnish YM report, Plastics Roadmap 2.0, which suggests that the replacement of fossil-based plastics should be prioritised. Bio-based plastics are swiftly becoming a strategic pillar in European industrial policy, as well, as confirmed in the new Bioeconomy Strategy. The strategy paves the way for bio-based plastics, which could mean biocomposites have the advantage of taking over conventionally plastic heavy industries, too. The regulatory development increasingly emphasises not only the replacement of fossil raw materials but also the ability to demonstrate material circularity. For biocomposites, the use of renewable fibres alone does not necessarily provide a regulatory advantage if the resulting material is difficult to identify, separate or recycle. Design-for-recycling, traceable material composition, controlled use of additives, recycled polymer content and reliable end-of-life information are therefore becoming increasingly important.

Chemical and environmental safety requirements are also becoming more relevant for composite manufacturing. Regulation (EU) 2025/2365 on preventing plastic pellet losses introduces EU-wide requirements for preventing, containing and cleaning up pellet spills across the plastics supply chain. In parallel, the REACH restriction on synthetic polymer microparticles has entered its reporting phase, with the first reporting obligations applying from 2026. These developments increase the importance of controlling polymer particle and pellet losses during compounding, extrusion, transport and other material-handling operations. A broad restriction of per- and polyfluoroalkyl substances (PFAS) is also under advanced evaluation under REACH. In March 2026, ECHA's Committee for Risk Assessment adopted its opinion supporting EU-wide action with targeted derogations, while the restriction process is still ongoing. Although this does not constitute a general PFAS ban at present, it creates an important future consideration especially for biocomposites with possible PFAS use in coatings.

One finding of the research, however, is that regulation is often written around traditional material categories, leaving biocomposites in a grey area. The business case for biocomposites could be improved by strengthening the policy activities, such as targets for recycled content and classification of material components and end-of-life options.

***The automotive industry*** Cars are excluded from the ESPR because they are already regulated through a comprehensive, sector-specific framework covering the full life cycle. A major regulatory development during the ABiCo project was the adoption of Regulation (EU) 2026/1738 on vehicle circularity and end-of-life management, which replaces the current End-of-Life Vehicles framework. The regulation strengthens requirements for vehicle reusability, recyclability and recoverability and introduces specific requirements concerning recycled materials. For plastics, minimum post-consumer recycled-content targets will be phased in, reaching 15% and later 25% of the plastic used in relevant vehicle types. Part of the recycled-content target is intended to be supplied from plastics recovered from end-of-life vehicles or vehicle components, supporting closed-loop recycling. The Regulation also strengthens requirements for dismantling, material and component information and circularity documentation. ELV, together with $CO_2$ regulations set strong quantitative targets and circularity requirements that are highly relevant to thermoplastic biocomposites, while the ESPR mainly plays a supporting role at component level.

***The construction industry*** The construction sector is mainly regulated by waste-focused legislation, especially the Waste Framework Directive, which requires at least 70% by weight for preparing for reuse, recycling and other material recovery of non-hazardous construction and demolition waste. Regulation primarily targets bulk material flows and end-of-life management, with less emphasis on product design. The influence of the ESPR is still limited and indirect, mainly via construction products rather than buildings. For biocomposites, however, the practical challenge remains the identification, separation and availability of suitable recycling pathways within heterogeneous construction waste streams. The new Construction Products Regulation (Regulation (EU) 2024/3110) establishes a revised framework for the placing of construction products on the EU market: the regulation strengthens product information and environmental-performance requirements and introduces a Digital Product Passport for construction products. For biocomposites, this increases the need for traceable material composition, durability data and end-of-life information, while highlighting the need for solutions that enable identification, separation, reuse and recycling at the end of a building's service life.

***The electronics industry*** The electronics sector combines product design regulation and waste legislation, with the ESPR expected to play a central and transformative role. The WEEE Directive sets a 65% collection target for e-waste, while the ESPR and RoHS drive requirements for durability, repairability, and safer materials. This creates a system in which circularity is addressed both upstream (design) and downstream (recycling). Compared with the automotive and construction sectors, electronics places a stronger emphasis on product-level circularity from the design stage onward, creating a regulatory environment where circularity is addressed throughout the entire product life cycle, from material selection and product design to collection, reuse and recycling.

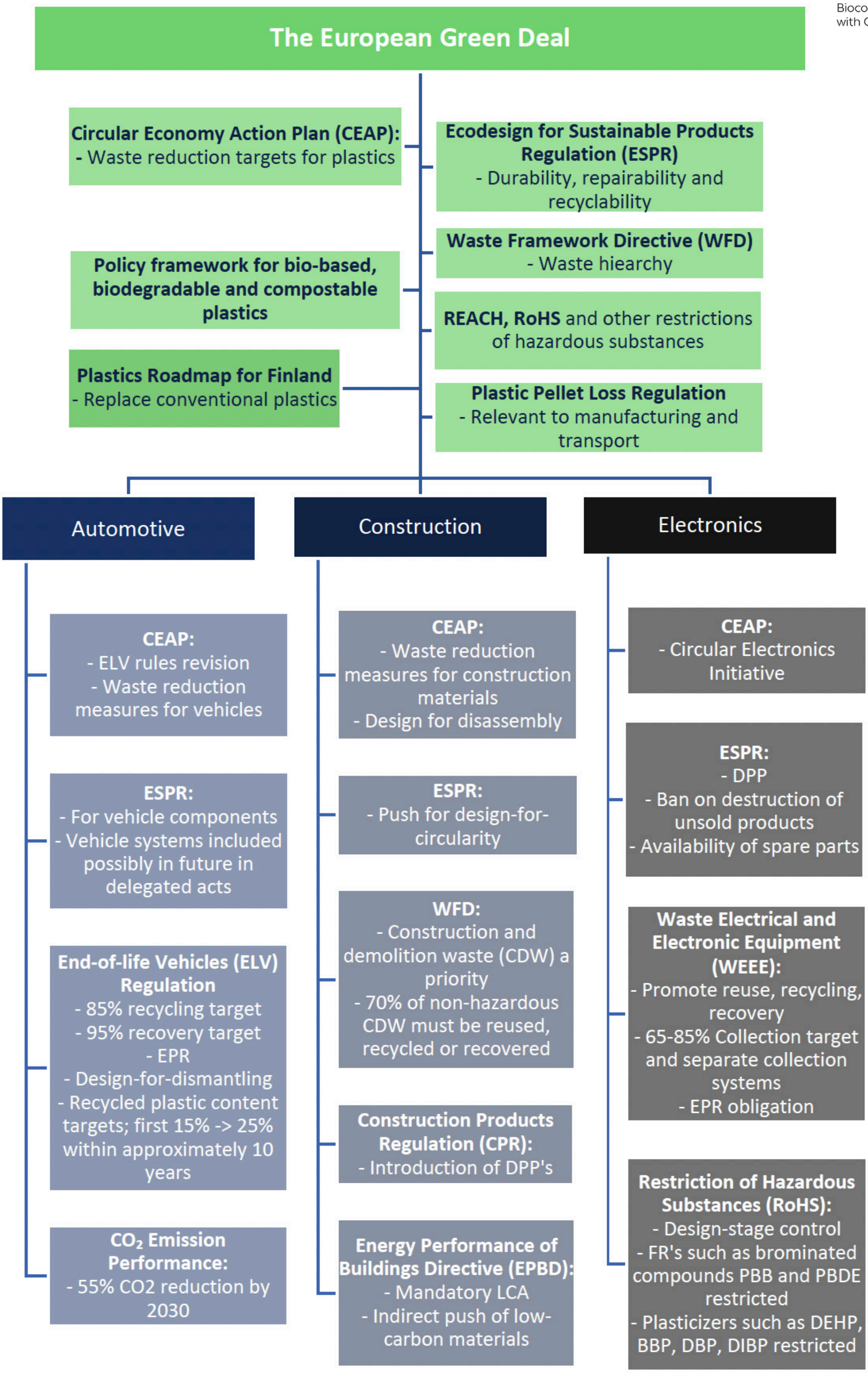


*Figure 48. An overview of current and future regulatory incentives and restrictions.*

The main findings of the regulatory review suggest that the success of advanced biocomposites depends on compliance with the evolving regulatory rules as much as it depends on the technical performance of such biocomposite products. The complexity of biocomposites and hazardous or potentially hazardous additives, the difficulty of dismantling and separating components, and other factors reviewed in T2.2 remain further challenges in biocomposite recycling. Functioning end-of-life systems could be reached through design-for-recycling concepts, disposal guides, and material transparency. Moreover, a classification or labelling of biocomposites could offer a significant push in efficient material flow utilisation.

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***Conclusively:***

- *Regulatory direction:* Green Deal, CEAP and Climate Law make circularity and resource efficiency the baseline. Plastics Roadmap and Communication from the EU support bio-based materials when recycling routes are credible and they are truly a better option.
- *Sector pressure points:* Automotive: ELV revision may require recycled plastic content and vehicle-level DPPs. Construction and electronics: DPPs, repairability, recyclability and safety requirements are strengthening.
- *Recycling & market enablers:* EPR is established in packaging, electronics, batteries, ELVs and oils, with possible expansion. Labels, material passports, secondary markets and harmonised classifications are needed to create pull.
- *ABiCo additive watch-outs:* Biochar: carbon-storage potential, but PAH/feedstock safety must be controlled. APP/DEPAL/MPP and phenolics: useful performance roles, but require ongoing REACH, RoHS, VOC and SVHC review.

## Publications

[Upcoming] Kärkkäinen, E., Zaikova, A., Kurvinen, A., Matrosov, A. & Immonen, K., 2026. Regulatory review: Upcoming regulation affecting biocomposite use and recycling in Finland., VTT Technical Research Centre of Finland. 43 p. DOI:10.32040/ABiCo.RegulatoryReview.2026. Biocomposites

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# Meta analysis of biocomposites

## Description

A meta-analysis was conducted on the connections between biocomposites' material development, processing, component design and system-level boundary conditions. The task of the meta-analysis was to compile the results of different work packages and, above all, to draw conclusions about where the most central and profitable applications of biocomposites in the future, so-called honey-pots, could be.

The use of biocomposites in industrial products has grown rapidly in recent years, especially in the construction, furniture, and consumer product sectors. The development is driven by several factors at the same time: climate and circular economy goals; new regulations, such as eco-design and producer responsibility; corporate responsibility requirements; and fluctuations in the price of raw materials and energy. Despite these, the large-scale introduction of biocomposites still faces significant technical, economic, and systemic challenges.

## Identification of most potential, so-called honeypot uses for biocomposites

In biocomposites, a strategic choice must first be made between biodegradability and recyclability. In structural and long-life applications, mechanical recyclability requires a known and limited material composition, functional material labelling, and uniform collection systems. Without these prerequisites, biocomposites in the future can end up in incineration or chemical recycling, which should be considered as last-resort recycling options.

The most promising properties for composite raw materials are: 1) they have a sufficiently large volume and continuous availability, 2) they are of uniform quality or can be obtained in a uniform quality (mixing/standardisation), 3) the price is affordable or at least predictable €/kg, 4) they are easy to process (drying, grinding, pelletizing), 5) they are compatible with the selected matrix (PP/PE/PLA, etc.), and 6) they do not compete strongly with higher value uses.

The meta-analysis shows that artificial intelligence and computational tools enable better and more efficient competitiveness and risk management of biocomposites, and help with predictive decision-making already in the early design phase of composites.

## Results

The key conclusion of the analysis is that the bottlenecks in biocomposites are not typically related to individual material parameters, process steps or component solutions, but to the connections between these factors. The variation in the properties of materials is transferred through processes to the component level and further to system-level requirements, such as certification, service life, and circular economy solutions.

**The most promising honey-pot groups of biocomposite products were recognised in the following segments:**

| Product category | Reasoning |
|---|---|
| Building materials, non-load-bearing components | High volume, easier standardisation and lower mechanical requirements |
| Furniture and interior | No heavy mechanical requirements |
| Packaging solutions | Short service life, collection and reuse quite easy |
| Automotive industry non-load-bearing parts | Standardisation less strict compared to structures, weight reduction |
| Consumer electronics, non-structural | Low performance requirements, environmental brand benefit |

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## Publications

Rahtola, M. (2026). Meta-analysis of biocomposites. https://urn.fi/URN:ISBN:978-951-827-533-9

# Technical feasibility synthesis from a techno-economic perspective

The ABiCo project provides sufficient evidence to conclude that the studied biocomposite material concepts are technically feasible at laboratory and early application-demonstration level, but not yet fully validated as industrial products. From a techno-economic assessment perspective, the main conclusion is that feasibility cannot be determined only through material price or isolated mechanical performance. Instead, technical feasibility depends on the combined maturity of raw material preparation, fibre or sawdust treatment, compounding, additive formulation, processing route, product geometry, quality control, durability, safety, recyclability, and the requirements of the selected end-use application.

WP1 created the main technical foundation for this conclusion. The project demonstrated that several renewable, recycled and bio-based raw material combinations can be processed into biocomposite compounds. Cellulose, sawdust, recycled polypropylene, bio-LDPE, PLA-based compounds, biochar additives, hydrophobized fibres, distillates and flame-retardant systems were prepared and tested. Altogether, the work showed that fibre pre-treatment, milling, compounding and moulding are technically possible, although each material route has different processing risks. For example, sawdust and cellulose can be incorporated into polymer matrices, but feedstock form, moisture sensitivity, fibre compatibility and additive loading strongly affect processability and final properties. This confirms that industrial feasibility is realistic only when raw material specification and pre-treatment are controlled.

Processing results also support technical feasibility, with limitations. Compounding, injection moulding, 3D filament production, 3D printing trials and foam injection moulding were tested. Injection-moulding trials indicated that the selected materials were mouldable, but some grades required higher pressure and showed risks such as short shots, flash, gas release or filling difficulties. 3D filament production and printing were possible, but brittleness, shrinkage, and print-head or print-bed limitations showed that additive manufacturing remains more suitable for prototyping and selected applications than as a general production route. Foam injection-moulding trials showed promising weight reduction potential while retaining mechanical properties better in some processing routes. These findings indicate that standard plastics processing routes can be used, but each product case requires material-specific process windows and production validation.

The project also produced important evidence on functional performance. Flame-retardant formulations were developed and screened, and several combinations showed improved fire performance. However, high additive loadings can compromise mechanical performance and increase formulation complexity. The project therefore identified the need to balance fire performance, filler content, mechanical properties and processability. This is highly relevant for TEA, because additional performance requirements such as fire resistance, UV stability, thermal stability, antimicrobial function or reduced VOC emissions may increase material cost, processing complexity and qualification burden. Technical feasibility is therefore strongest in applications where the required property profile can be achieved without excessive additive loading or highly complex formulation design.

WP3 strengthened the feasibility assessment through long-term property, safety and application-related testing. Acoustic emission testing, mechanical testing, thermal stability testing, weathering studies, VOC emission studies, biochar safety screening and antimicrobial testing provided evidence that the developed materials can be evaluated against relevant technical and safety criteria. Some results were positive, such as no major concerns in selected biochar cell-model testing and reduced VOC emissions after post-treatments. At the same time, ageing, UV resistance, weathering and long-term stability remain partly unresolved. This means that the materials are promising, but long-service-life applications, exterior use, and regulated or safety-critical products still require additional validation before industrial deployment.

WP2 added a necessary system-level perspective. Circular design, end-of-life studies, LCA work and AI-supported modelling showed that the technical feasibility of biocomposites cannot be separated from recycling, sorting, identification, take-back logic and life-cycle performance. Mechanical recycling appears to be the most realistic near-term route, but it requires separation of compatible polymer matrices and better identification methods. Because current biocomposite waste streams are fragmented and low-volume, closed-loop or take-back systems may be more realistic than broad post-consumer recycling in the short term. This is important for TEA because circularity can improve the business case only when material flows, collection logic and product ownership models are designed early.

The TEA work did not create an independent technical feasibility test programme. Instead, its role was to synthesize the technical evidence generated in WP1, WP2 and WP3 and translate it into scenario-based decision logic. This is appropriate for the project stage, because the economic feasibility of biocomposites depends on technical assumptions that are still application-specific and partly preliminary. The TEA findings therefore support a conditional feasibility conclusion: no clear technical blocking barriers were identified from available project results, but full industrial feasibility cannot yet be claimed without final demo-product integration, scale-up trials, production-rate assumptions, durability validation and application-specific cost modelling.

Overall, ABiCo shows that advanced biocomposites based on cellulose, sawdust, recycled polypropylene, bio-LDPE, PLA and selected additives can be technically feasible for selected product concepts. The strongest near-term opportunities are likely in applications in which existing plastics processing infrastructure can be used, material requirements are moderate or clearly defined, and circular design can be connected to controlled material flows. The main remaining technical risks are long-term durability, UV and thermal stability, additive complexity, feedstock variability, recycling separation, and the weak link between laboratory results and industrial product qualification. From a techno-economic perspective, the project therefore supports further development, but the next phase should focus on narrowing the application scope, validating selected formulations in realistic production conditions, and connecting technical performance directly to cost, quality, lifetime and end-of-life scenarios.

## Literature review on biocomposites

The literature review for ABiCo Task 3.3 shows that biocomposite techno-economic assessment is still a fragmented evidence area. The reviewed evidence base covered 32 studies, but only a small share provided direct techno-economic assessment evidence. Most sources were reviews, experimental studies, LCA/LCC studies, or methodological papers. This means that the


*Figure 49. Literature review synthesis for ABiCo Task 3.3 techno-economic assessment.*

literature is useful for identifying cost drivers, technical barriers, adoption conditions and relevant indicators, but it does not yet provide a robust set of directly comparable plant-scale TEA benchmarks for ABiCo-type biocomposite applications.

The strongest relevance for ABiCo is found in studies dealing with polyolefin matrices, especially PP, recycled PP, PE, HDPE, LDPE and bio-PE, combined with wood-based or cellulosic fillers such as sawdust, wood flour, bleached softwood kraft pulp and cellulose. This aligns well with ABiCo's material development focus. Evidence from natural fibres, agricultural residues, recycled plastics, recovered cellulose and biochar is also useful, but comparability is limited because fibre type, filler loading, particle size, pre-treatment, additive package, processing route and product geometry vary strongly between studies.

The reviewed literature repeatedly identifies five technical requirements as decisive for adoption: mechanical strength and stiffness, moisture and water resistance, thermal and fire performance, fibre–matrix adhesion, and processability. These requirements should be treated as interdependent TEA variables rather than isolated material properties. For example, a low-cost filler can improve material economics only if drying, feeding, compounding, moulding, surface quality, durability and quality assurance remain acceptable at the intended production scale.

The main barriers are consistent with the ABiCo project findings. Moisture sensitivity, long-term durability, fibre and feedstock variability, need for drying or pre-treatment, interfacial adhesion problems, scale-up uncertainty, investment needs, and supply-chain reliability remain the most important risk areas. These barriers are especially relevant for applications where biocomposites compete with established materials such as virgin plastics, aluminium, PVC, wood, MDF or conventional composites.

From a TEA perspective, the literature uses many different indicators: material price, €/kg, part cost, CAPEX, OPEX, NPV, ROI, IRR, payback time, break-even volume, LCC, GWP, $CO_2$-eq, eco-efficiency, sensitivity analysis and scenario benchmarking. However, these indicators are used inconsistently. Many studies report technical properties without production economics, while others provide cost models without sufficient application-specific validation. Therefore, ABiCo should avoid presenting TEA as a single final profitability calculation. The more reliable contribution is a transparent scenario-based decision logic that shows how material formulation, process route, product requirements, production volume, feedstock price, scrap rate, recycling route and benchmark material affect feasibility.

The main conclusion is that biocomposite adoption depends on the balance between performance, processing compatibility, feedstock reliability, application fit and circularity. The literature supports the feasibility of PP/PE-cellulosic biocomposites in selected applications, especially extrusion-relevant and profile-type products, but it also confirms that final adoption requires application-specific validation. For ABiCo, the clearest evidence gap is the limited availability of directly comparable, plant-scale and product-specific TEA data. This makes the current TEA results suitable for preliminary feasibility assessment, bottleneck identification, and future project planning, but not yet for investment-grade economic conclusions.

## Market and manufacturing benchmark findings for ABiCo TEA

The market screening suggests that the most relevant TEA comparison for ABiCo is not "biocomposite versus plastic" in general, but specific product systems in which feedstock, processing route, product geometry, warranty, maintenance and end-of-life route are already commercially defined. The strongest benchmark category remains WPC/profile-extrusion products: decking, facade profiles, fencing, rails and other continuous profiles. These products match ABiCo's interest in PP/PE or bio-PE matrices with sawdust, wood flour or cellulose fillers, and they also provide clearer price, equipment and process benchmarks than isolated laboratory material studies.

Existing WPC products show that industrial feasibility is already proven, but mainly where the product is standardised and produced at sufficient volume. Silvadec's 2024 EPD describes composite deck boards made from wood flour and HDPE, with a declared function of covering 1 m² of outdoor surface for 25 years. The declared product mass is 25.2 kg/m², including wood flour, HDPE, regenerated HDPE, additives and fillers. This gives ABiCo a useful benchmark for translating material formulation into product-level mass, lifetime and LCA/TEA assumptions. InoWood provides another relevant European benchmark: its EPD describes WPC profiles used for facades, terraces, and fencing, made from recycled plastic and timber particles, with 25-year service-life assumptions and a production system using six continuously operating extrusion lines.

From a manufacturing perspective, WPC is a mature industrial processing route rather than an experimental niche. Coperion describes WPC production as a complete compounding system including material transfer, feeding, filling, reinforcement, devolatilization, pelletizing, conveying and packaging, which is important for ABiCo because the cost is not only the extruder, but the full material-handling and quality-control chain. Bausano similarly presents WPC profile extrusion as a twin-screw process capable of combining PVC, PE, PLA or PP with wood or natural fibres; its WPC lines are described as suitable for profiles with high natural-fibre loading, including up to 100 phr in one description and up to 80% wood powder in another.

Indicative equipment price checks show very wide ranges and should be treated only as preliminary CAPEX inputs. Public listings suggest used twin screw extruders around €24,000–97,000, new pro cess extruders roughly €20,000–200,000 depending on scale and automation, and simple single-screw marketplace listings around €10,000–100,000. These figures exclude several cost drivers relevant to ABiCo: fibre drying, dosing, compatibilizer/additive handling, die and calibration tooling, cooling, haul off, cutting, scrap handling, QC testing, installation, commissioning, labour and maintenance.

Product price benchmarks also vary strongly. Public European examples show WPC boards from low-cost hollow planks to higher-value solid or capped systems, with indicative market ranges such as 3–8 €/running metre for hollow WPC, 5–15 €/running metre for solid WPC, and 7–20 €/running metre for sheathed WPC; one InoWood retail example lists approximately 55 €/m² including VAT. Therefore, ABiCo TEA should avoid one fixed material-price conclusion and instead model price thresholds by product class, lifetime, processing yield and incumbent alternative.

The clearest commercial benchmark remains US based Trex, where the business model combines recycled PE film, reclaimed wood, high-volume extrusion, durable decking, low maintenance and long warranties. Trex reports decking made from up to 95% recycled and reclaimed materials and describes its products as lower-maintenance than wood over deck lifetime. For ABiCo, this supports a practical conclusion: biocomposite feasibility improves when side-stream feedstock, extrusion scalability, product standardisation, warranty logic and circular collection are designed together, not treated as separate technical issues.

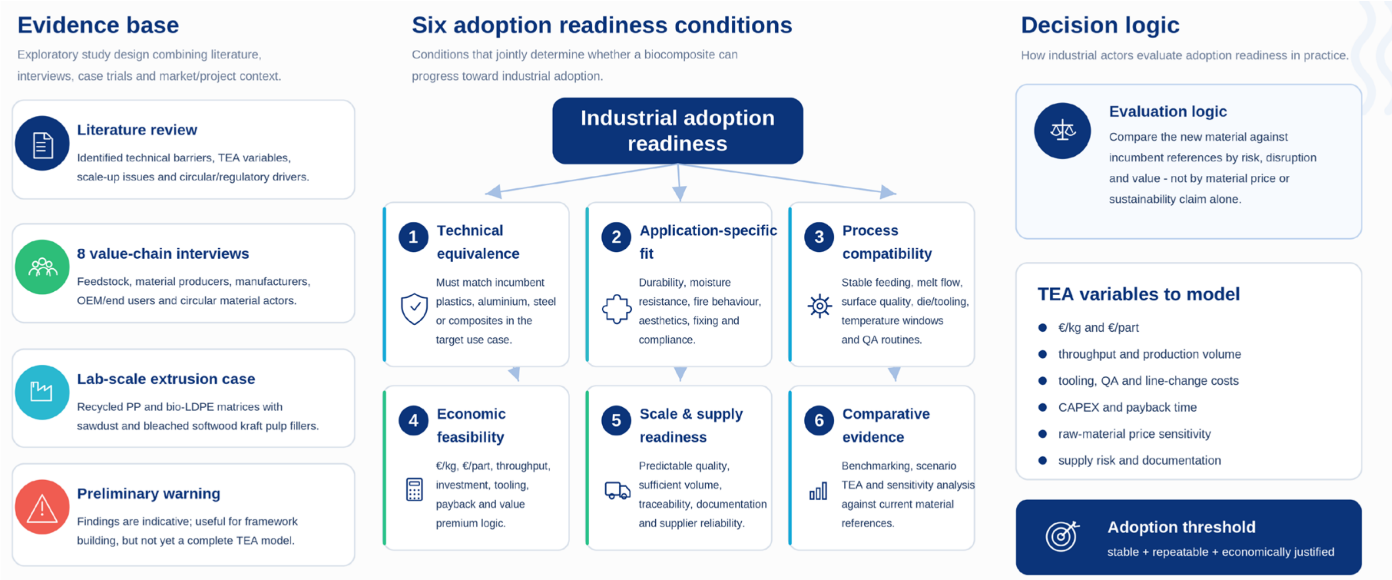


*Figure 50. Visual summary of the conference paper Preliminary Techno-Economic Factors Shaping Industrial Adoption of Biocomposites. The framework synthesizes the ABiCo literature review, laboratory results, industrial interviews and market benchmarking into a structured model describing the key conditions influencing industrial adoption and future techno-economic assessment.*

## Techno-economic assessment tools for future biocomposite development

Techno-economic assessment (TEA) in ABiCo should be seen as a transparent decision-support method rather than a single calculation tool. Future biocomposite development cannot be evaluated only through material cost or individual material properties. Economic feasibility depends on the combined effect of raw materials, formulation, pre-treatment, compounding, processing route, additives, product design, quality requirements, lifetime performance, recycling route and customer-specific application logic. ABiCo has produced relevant data for this type of TEA logic, including results on cellulose, sawdust, recycled polypropylene, bio-LDPE, PLA-based compounds, biochar additives, flame-retardant systems, 3D printing, injection moulding, VOC emissions, safety screening, ageing, weathering and mechanical performance. The project has also connected these results with circular design, end-of-life studies, LCA, regulation, company interviews and benchmark screening. This shows that commercial feasibility depends on matching a material route with a credible product case, not only on producing a technically valid compound.

A future TEA framework for biocomposites should be modular. The first layer should be a transparent spreadsheet or database model for material recipes, raw material prices, processing parameters, yields, scrap rates, energy use, labour, equipment assumptions, benchmark prices and uncertainty markings. This layer is most useful for early screening, cost hotspots, threshold values and missing data.

The second layer should use open-source and low-cost tools such as DWSIM, COCO, Python, R, MATLAB and Scilab, where an additional calculation structure is needed. These tools can support simplified mass balances, energy balances, sensitivity analysis and scenario comparison for drying, compounding, extrusion, injection moulding, 3D printing, recycling logistics and take-back loops.

The third layer includes commercial process simulation and modelling tools such as Aspen Plus, Aspen HYSYS, SuperPro Designer, ProSimPlus and gPROMS. These tools are relevant when the process route is more mature and higher-fidelity modelling is justified. Their value is strongest for selected process-block validation, equipment sizing, utilities and investment-level assumptions.

The fourth layer should link TEA to environmental assessment and circularity. ISO/TS 14076:2025 is relevant because it defines environmental techno-economic assessment as a combined economic and environmental assessment approach. LCA tools and databases such as openLCA, ecoinvent, Sphera/GaBi, GREET, PlasticsEurope Eco-profiles and Environmental Footprint datasets can support this layer. This is important because a biocomposite route may be economically attractive yet less compelling if durability, recyclability, additive burden or end-of-life treatment reduce its environmental value.

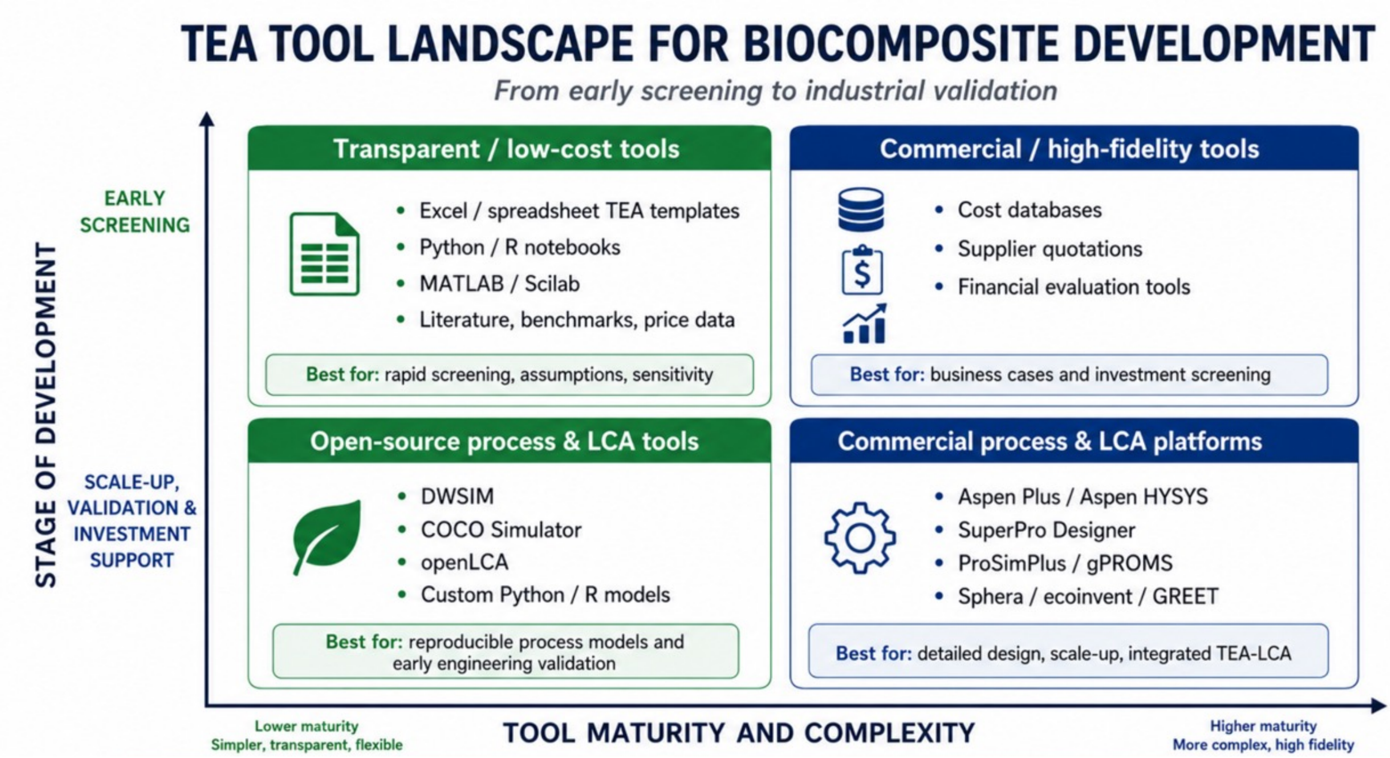


*Figure 51. TEA tool landscape for future biocomposite development. Transparent spreadsheet and open-source tools support early screening and assumption tracing. Commercial process simulators and professional LCA tools become more relevant when process routes, production volumes and product boundaries are mature enough for higher-fidelity validation. The main future need is an integrated ABiCo-type scenario model connecting formulation, processing, product performance, circularity, LCA and business logic.*

The main conclusion is that future biocomposite TEA should not copy a generic chemical plant TEA model without adaptation. ABiCo follow-up work needs a traceable scenario model that connects formulation, processing, product performance, circularity, LCA and business logic. Each input should be marked by evidence type: measured ABiCo data, literature value, supplier quotation, market benchmark, expert assumption or unresolved estimate. This would make assumptions visible, reduce overclaiming, and support better decisions for future demonstrations.

Advanced Biocomposites with Circular Design

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# Company statements – Benefits for participants

## Pihla Group

Inwido is one of Europe's leading window and door groups, with 35 business units and a strong presence in Sweden, Finland, and the UK. Pihla Group represents Inwido's Eastern business area, operating nine production sites in Finland under brands such as Pihla, Tiivi, Sydänpuu, Profin, and Klas1.

Within the ABiCo project, Pihla Group focused on low-carbon materials, material substitution, and increasing the share of recycled content, with a particular interest in alternatives to aluminium and plastics. While the project emphasised new material development – an area where the company's direct contribution was more limited – it provided valuable insights into life-cycle assessment (LCA), circular economy principles, and material circularity metrics.

Overall, ABiCo supported Pihla Group's transition from a compliance-driven approach towards a more data-driven integration of low-carbon and circularity considerations in product development and sourcing. The project's outcomes are expected to guide future development work and strengthen the role of sustainability in material selection and supplier collaboration.

**Timo Nissinen**
Technology Director
Pihla Group Oy

## Meyer Turku

Meyer Turku is one of the world's leading builders of large cruise ships and a key industrial player in Finland's maritime cluster. As an ABiCo project partner, Meyer Turku contributed valuable expertise in the requirements of the marine environment, bringing insights into topics such as durability, fire safety, seawater resistance, UV exposure, and customer expectations for high-quality ship interiors.

The company joined ABiCo to support its long-term ambition of developing more sustainable and ultimately carbon-neutral vessels. Although a parallel internal composite development project did not progress as originally planned, ABiCo provided an important opportunity to explore the potential of bio-based composite materials in maritime applications. During the project, Meyer Turku identified several aluminium-based ship components that could potentially be replaced with ABiCo materials in the future.

Beyond material development, the project offered new perspectives on circular design, life-cycle sustainability assessment (LCA/LSA), and circularity measurement methods such as the Material Circularity Indicator (MCI). These themes broadened the company's understanding of how circular economy principles can be integrated into product development and decision-making processes.

ABiCo also strengthened connections between Meyer Turku and the research community, creating a foundation for future collaboration. Looking ahead, the company sees clear potential for the application of biocomposites in cruise ship construction and considers the project's insights into circular design and sustainability assessment particularly valuable for future development efforts.

**Sani Ojala**
Classification engineer
Structural design
MEYER TURKU Oy

## Brightplus

Brightplus joined the ABiCo project to strengthen its capabilities in low-carbon, bio-based materials and to further develop its BrightBio® platform. Key drivers included improving material performance, recyclability, and the utilisation of industrial side-streams in scalable solutions.

The project provided valuable knowledge on bio-based raw materials, additive functionalities, and their impact on processing and end-use performance.

It also enhanced the company's system-level understanding and supported ongoing product development.

ABiCo enabled collaboration with research and industry partners, strengthening networks that are important for future innovation and validation of new solutions.

Looking ahead, Brightplus sees opportunities to further develop and scale the results, while continued collaboration remains essential. The growing demand for sustainable materials supports further development in this area.

Overall, the project has supported Brightplus' strategic development and demonstrated the value of collaborative innovation in advancing sustainable material solutions.

**Milja Hannu-Kuure**
Managing Director
Brightplus Oy

## NG Nordic, Circo® plastics

NG Nordic is a leading Nordic circular economy company. Within NG Nordic, the Circo® business focuses on transforming post-consumer plastic packaging waste into high-quality recycled plastic raw materials and compounds for industrial applications. The ABiCo project, carried out within the ExpandFibre Ecosystem, aligned well with the business's interest in developing biocomposite solutions and expanding the application potential of recycled polymer materials.

NG Nordic participated in the ABiCo project and contributed to the project planning phase, as well as to the steering group work throughout the project. The project provided an opportunity to explore how recycled polymers and bio-based materials can be combined into circular material solutions for demanding applications and to support the development of practical industrial use cases.

For Circo®, the project offered valuable perspectives on circular design, material circularity assessment, life-cycle thinking, and the future requirements for recycled-material-based products. As a supplier of recycled raw materials, NG Nordic particularly appreciated the opportunity to participate in discussions across the value chain, from material development to end-use applications and end-of-life considerations. The project also provided a useful forum for collaboration between industrial and research partners.

The results of ABiCo can support future business case development and the introduction of new circular material solutions in both domestic and export markets. The project strengthened NG Nordic's understanding of the opportunities and challenges related to recycled plastic biocomposites and their role in the transition towards a more circular economy.

**Kari Aaltonen**
Product Line Specialist, Plastics Recycling
NG Nordic

# Future perspectives

The ABiCo project took place in a time frame when biocomposites and the type of researched materials are being requested by industries. In addition, during the project, the European Commission launched the new Bioeconomy Strategy (European Commission, 2025), in which circular and sustainable business models are encouraged. The project also showed that to harness the full potential of biocomposites, there is a need for further application-specific development work that spans the value network.

The transition towards more sustainable materials has accelerated interest in biocomposites as viable alternatives to conventional, fossil-based materials in various industrial applications. Biocomposites are a growing trend in various applications in several industrial sectors, such as the automotive, construction, and electronics sectors. One of the primary motivations behind the shift towards circular business models is the need for resilience in uncertain market conditions. Fluctuations in raw material prices and concerns over long-term resource availability have exposed vulnerabilities in traditional linear supply chains. By reducing dependency on virgin materials and promoting the use of, for example, recycled inputs, circular approaches enhance supply security and can affect cost structures. Regulatory frameworks and investor expectations are also increasingly steering industries towards circularity. Investors are also placing greater emphasis on sustainability performance, and companies adopting circular business models demonstrate proactive leadership. Circular solutions are a pre-requisite in raw material sourcing, thus biocomposite products can strengthen brand identity, build trust, and align with customer values. The adoption of circularity fosters innovation and a competitive advantage for companies. This shift not only enhances technological and organisational innovation, but it also opens opportunities for new market entrants and ecosystems built around sustainable materials.

## The field of biocomposites is evolving

As novel industrial application areas and the demand for biocomposites are evolving, a lot of research and development actions are being done in the field. The development of various material compositions and raw material bases are being tested. Geographically availability of different fibre or recycled plastic sources affect the development trends and new quality experimentations. Certain material trends that have been discovered are the development of high-strength natural fibre-reinforced biocomposites and hybrid bio-synthetic composites. Biocomposites integrated with nanocellulose for better performance are also being tested. Developing recyclable thermosets and thermoplastic biocomposites to improve life-cycle sustainability is one area of interest. There is increasing vertical integration, or the use of one's own raw materials (such as hemp or flax) for controlled quality and supply. Start-ups are experimenting with biocomposites based on agricultural waste (e.g. coconut coir, rice husk, and banana fibre for cost-efficient, high-performance bio-fillers). The biodegradable polymers segment is expected to grow fast in biocomposites. Polymers such as PLA (polylactic acid) and PHA (polyhydroxyalkanoates) are gaining popularity in single-use products as technological advancements improve the mechanical performance and processability of biodegradable polymers.

Biocomposite value networks consist of both global material companies and regional players. Key players dominate the supply of engineered natural fibres and resins. Start-ups and small manufacturers serve local or niche markets. Strategic partnerships between material producers and end-user industries are formed and increasing. From a technology point of view, extrusion currently has the biggest share of processing. The injection-moulding segment is expected to grow and it is being increasingly adopted in the automotive, electronics, and consumer goods industries for producing intricate parts. Injection moulding is enabling the transition from conventional plastics to greener alternatives. Advancements in tooling and mould design are also expanding the range of applications for injection-moulded products.

## Circular design opens routes to a new business approach

The circularity of materials – both biological and technical material cycles – becomes fundamental to how the business model is conceived. As circular design is incorporated as the central point for product development, raw material suppliers, biocomposite manufacturers, technology and tooling providers, and final product producers must actively share knowledge and coordinate development efforts. This collaboration extends to end users, whose specifications and quality expectations ultimately define market acceptance. Close co-operation along the supply chain enables better alignment of material properties, processing methods, and end-user requirements, while also fulfilling sustainability goals. Design and material choices play a decisive role in the entire system. As new materials are developed, product designers need to be familiarised with them and their properties. Designers together with end users are an important target group in new product development. This engagement extends beyond individual designers to include designer associations and organisational design, research and development (R&D) departments. A key is the ability to identify and serve new customer groups and market segments and find value-creating factors for them. By fostering collaboration with these groups, companies can accelerate the adoption of new types of biocomposites and ensure that material innovations are effectively translated into new product applications. Cross-sector partnerships, vertical integration of supply chains, experimentation, and new ways of creating and delivering value become key. Achieving a company-level strategic fit within the broader ecosystem is increasingly important, as organisations must position themselves in ways that complement other actors within the value network. This involves understanding interdependencies, identifying partnership opportunities, and aligning internal strategies with external ecosystem dynamics. Companies that successfully integrate into these networks are better equipped to leverage shared knowledge, access new markets, and discover emerging business potential.

There are also some challenges in applying circularity to biocomposites. Regulations governing recycled plastics and bio-based materials can vary significantly between applications. Increasingly ambitious recycling targets place pressure on industries to meet strict performance and recovery requirements. While these regulations aim to accelerate the transition towards circularity, they can also create compliance challenges for emerging materials, such as biocomposites, where standards and certification systems are still evolving. Recycling processes themselves also present significant challenges. As the production and use volumes of biocomposites in different sectors grow, there is a need for recycling systems capable of handling diverse material compositions. Biocomposites often consist of complex combinations of natural fibres and polymer matrices, which can complicate separation and recovery processes. This gap restricts the ability of companies to implement circular business models at scale and highlights the need for further innovation in material design and product development. Recycling technologies must be further developed and optimised to ensure efficient material recovery, maintain quality, and minimise environmental impact. Closely linked to recycling is the issue of data gaps and material traceability. Effective circular business models rely on accurate information about material composition, origin, and life-cycle history. However, in many cases, such data is incomplete, inconsistent, or unavailable. This lack of transparency makes it difficult to track materials through the value chain, assess their suitability for reuse or recycling, and ensure consistent quality. Finally, reverse logistics systems for collecting, sorting, and returning materials at the end of their life remain underdeveloped. Unlike traditional linear supply chains, circular models depend on efficient reverse flows of products and materials. However, infrastructure for the collection, transportation, and processing of biocomposite waste is still limited in many industries and regions. Developing these reverse logistics chains requires investment, stakeholder coordination, and supportive policy frameworks.

The transition towards a circular business model is not defined by a single solution or model, but rather by the ability of companies to adopt and combine multiple circular strategies simultaneously. Organisations develop portfolios of complementary business models, such as reuse, recycling, product-service systems, and material recovery. This approach allows companies to capture value across different stages of the life cycle. By offering products with lower environmental impacts, companies can support their customers – both business clients and end users – in achieving their own sustainability targets. This alignment with customer goals not only enhances value propositions but also strengthens market positioning. Via value network collaboration, there is a place for innovation that is distributed across all actors involved – in material production, processing, manufacturing, and tooling technologies. Each stage offers opportunities for technological advancement that collectively support circularity in the targeted industry sector. The use of industrial side-streams presents significant potential for improving raw material availability in biocomposite production. By utilising by-products and waste-streams from other industries, companies can reduce reliance on virgin resources and enhance resource efficiency. This approach can benefit from industrial symbiosis and vertical integration, where co-located or interconnected industries exchange materials, energy, and knowledge to create mutual benefits.

The development of closed-loop systems represents one of the developing elements for the sector. As the use of biocomposites increases and recycling volumes reach critical mass, it becomes feasible to establish recycling loops with more controlled quality data and in which materials are continuously recovered and reintroduced into production. There is a need for the development of advanced material recognition and sorting technologies at an industrial scale. Efficient identification and separation of materials are needed to ensure high-quality recycling and enable circular flows. The end-of-life phase is emerging as a critical area for innovation, opening new business opportunities in material flow management, digital tracking, and automated sorting systems.

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