



CALiMERO

IMPROVING BIO-BASED INDUSTRIES LIFE CYCLE SUSTAINABILITY

D5.2

Potential cross-sectorial solutions

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LIST OF ACRONYMS

CE	Circular Economy	IS	Industrial Symbiosis
CHP	Combined heat and power	LSL	Laminated Strand Lumber
D	Deliverable	PR	Periodic Report
EU	European Union	WP	Work Package
GHG	Greenhouse Gas		

PROJECT INFORMATION

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List of participants:

Partner No.	PARTICIPANT ORGANIZATION ACRONYM
1 (Coord.)	Contactica CTA
2	WeLOOP WELOOP
3	European Cellulose Insulation Association ECIA
4	Swedish Environmental Research Institute IVL
5	Neovili NEOVILI
6	Cesefor CESEFOR
7	Luxembourg Institute of Science and Technology LIST
8	Technical University of Denmark DTU
9	Techtera TECHTERA
10	Essity ESSITY
11	BIM Kemi AB BIMKEMI
12	Ereks garment EREKS

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Authors:	Eduardo Entrena Barbero (CTA), María Gallego Fernández (CTA), Tamara Coello (CESEFOR), Federico Busio (LIST), Pauline Guillon (TECHTERA), Pelin Birsen (EREKS), Bilgesu Altuncan (EREKS), Milena Amaral (Neovili), Mate Saric (IVL), Emma Moberg (IVL), Pernilla Cederstrand (ESSITY), Margarida Vidinha (WELOOP), Naeem Adibi (WELOOP), David Stimm (ECIA), Juho Laaksonen (ECIA), Sahar Safarianbana (IVL)
Abstract:	<p>In the search for alignment with the Circular Economy (CE) model in today's society, bio-economy industries play a key role due to the nature of their raw materials used. In this regard, bio-based materials facilitate CE initiatives such as reducing raw material depletion or avoiding waste generation through their reuse or recycling, thus contributing to the expansion of production and consumption loops. In addition, all these CE principles can be enhanced taking into account the Industrial Symbiosis (IS) concept, which looks forward to collaboration between entities in the sense that a waste of one company can be transformed into an input for another.</p> <p>Under this context, one of the CALIMERO project aims is to enhance sustainability in 5-target industrial bio-based sectors, which include construction, textiles, woodworking, chemicals, and pulp and paper in a cross-sectorial way. To this end, a series of cross-sectorial solutions with potential for sustainable improvement were identified through a top-down approach based on a literature review. This was accompanied by a bottom-up approach through collaboration between academic and industrial partners to narrow down the set of solutions identified for the ten case studies selected for analysis in the project.</p> <p>As a summary of the fruitful information obtained, the cross-sectorial solutions identified have been collected in a table differentiated per type of common synergies (i.e., governance synergies, shared infrastructure and common services), as well as sector-dependent synergies (in material, water or energy resources terms). Therefore, the consultation of this report by both industrial and academic stakeholders of the bioeconomy can be used not only for sustainability improvement proposal consultancy, but also for further exploring the solutions identified based on the future prospects highlighted.</p>

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1 INTRODUCTION

1.1 Industrial symbiosis and bio-economy in the circular economy context

Industrial Symbiosis (IS) can be understood as a strategy compendium based on collaboration between companies, where the unwanted outputs (in the form of waste or by-products) of one industrial facility are used as raw materials for another, in order to optimize resource use while generating economic, environmental and/or social benefits (Kosmol and Esswein, 2018). The concept of IS is inspired by the natural sciences, where symbiosis refers to the sustainable coexistence of species that provide mutual benefits (Fraccascia et al., 2021). In fact, this constitutes a subset within the industrial ecology, with one widely accepted definition being that of Chertow (2000), who describes IS as the engagement of traditionally separate entities in a network approach to competitive advantage through the physical exchange of materials, energy, water and by-products.

Nevertheless, it is noteworthy that these exchanges can occur over long distances, as highlighted by Zhang et al. (2015), suggesting that proximity is not a prerequisite for the development of symbiosis. Moreover, the inflows/outflows exchanged can be not only physical things, but also share specific knowledge or the granting of the use of a shared space (Mirata and Emtairah, 2005). In this context, Azevedo et al. (2021) identified different types of exchanges, such as intra-company, inter-company, eco-industrial parks and urban-industrial interactions. There are several key drivers for fostering such interactions and thus moving towards IS. These include economic and business impacts, eco-innovation, regional economic development, resource security, energy security, and climate change mitigation. Therefore, taking into account all these factors, IS has been recognized as playing a key role in the pursuit of paving the way for the implementation of a Circular Economy (CE) at the local level (Cecchin et al., 2020). The foregoing is based on the fact that the collaborative network between companies promotes resource use efficiency and waste reduction, in addition to encouraging innovation, creating new market opportunities, enhancing corporate image, and ensuring regulatory compliance, thereby contributing to environmental and social sustainability (Domenech et al., 2018).

Currently, there is a growing interest in IS, as evidenced by the increasing number of scientific publications on the topic, apart from the successful practical cases where companies have improved their sustainability through the implementation of a series of collaborative actions (Mallawaarachchi et al., 2020). The first well-known and widely discussed example was an industrial network established in Kalundborg (Denmark), where industries began to cooperate intensively to reduce costs by improving waste management and using fresh water more efficiently. In addition, Neves et al. (2020) showcase several success stories where IS practices, such as resource sharing or reducing waste disposal, have led to significant reductions in carbon footprints.

In the search for alignment with CE principles, both the bio-economy industry and IS are proving to be of paramount importance. In this regard, Hildebrandt et al. (2019) describe two main ways in which IS can be implemented in bio-based systems. On the one hand, the adaptation of existing production infrastructures and networks. An example of this could be the transformation of conventional refinery sites into eco-industrial parks, where synergies between biomass suppliers, biotechnology and chemical companies, as well as waste facility operators, facilitate the transition to an IS model. On the other hand, the creation of a new pilot and demonstration plant (e.g. supported by governmental economic initiatives), operated synergistically by different industries. Therefore, one of the most promising aspects of the link between the IS and the bio-based industry is the opportunity to test process scalability, as the principles and strategies of the IS are largely associated with industrial-scale production, while the bio-based industry is still in its early stages of development.

According to the applicability potential of the IS model, since the launch of the European Green Deal in 2019, several ambitious policies have been promoted that focus on closing life cycle loops of products through increased reuse and recycling actions (Wadström et al., 2021). In this line, the SCALER project provides an overview of European Union (EU) policies that directly or indirectly enable IS for processes. Depending on the

focus, different policy levels were identified. Most policies have a global, European, or national impact (i.e., macro level), such as EU directives and regulations, including the Circular Economy Action Plan and the EU Waste Framework Directive. There are also policies related to the regional level (i.e., meso level), of which the following can be highlighted: practices guidelines and government financial support for eco-industrial parks. At the local or micro level, although specific policies may be lacking, there are key actors who facilitate the implementation of IS, e.g., intermediaries providing services through brokering and exchange platforms (Karagkounis, 2020). Artola et al. (2018) have identified various policy instruments in this regard that promote IS, classified them into direct and indirect support. Direct support includes strategic investments, regional networks, subsidies, apart from research and development initiatives. Indirect support encompasses regulatory instruments like waste and eco-design standards, as well as economic instruments such as landfill and resource taxes and voluntary approaches like green public procurement and training programs.

In summary, IS yields significant environmental and economic benefits, including resource and raw material savings, reduction of greenhouse gas (GHG) emissions and decreased waste sent to landfills and incineration. Although in some cases the costs of creating symbiosis can be high (e.g., potentially requiring the construction of necessary infrastructure or acquisition of new machinery), the overall balance is usually positive (Neves et al., 2020).

1.2 Aim and objectives

The CALIMERO project, funded by Horizon Europe, aims to enhance sustainability in 5-target industrial bio-based sectors, which include construction, textiles, woodworking, chemicals, and pulp and paper. Therefore, based on the IS concept, the main goal of this deliverable is to compile several cases of cross-sectorial strategies within the bio-based sectors of the CALIMERO project. In this regard, different types of IS can be identified; on one hand, there are sector-independent strategies, such as the exchange of knowledge and the sharing of infrastructure and services (Freitas and Magrini, 2017). On the other hand, some approaches may vary depending on the industry, as each consumes different resources and produces different by-products or waste. Within this exchange of resources, distinctions can be made among the exchange of materials (raw materials, by-products and waste), water and energy (Chen et al., 2022). Likewise, in order to avoid double counting, the identified cross-sectorial solutions with sustainable improvement potential have been assigned to the bio-based sector that produces the by-product or waste to be used as raw material in any other of the remaining 4 bio-based sectors of the CALIMERO project.

With such an aim, a preliminary identification of the range of cross-sectorial solutions with potential for sustainable improvement is carried out through a top-down approach based on a literature review. After this, the focus is put on the case studies of the CALIMERO project in order to narrow down the available options. For this purpose, a bottom-up approach is followed, in which the academic partners hold internal meetings with the corresponding industrial partners. Due to the fact that all belong to the same consortium, it has been possible to obtain reliable primary information, although it is usual to face a number of drawbacks when conducting this type of approach, related to the willingness of companies to share inventory data, confidentiality issues and time constraints (Patricio et al., 2022).

A visualization of the potential interrelationships between the 5-target bio-based sectors of the CALIMERO project in terms of cross-sectorial sustainability solutions is shown in [Figure 1](#). Moreover, the main characteristics of each bio-based sector are displayed regarding the number of case studies and the academic and industrial partners involved.

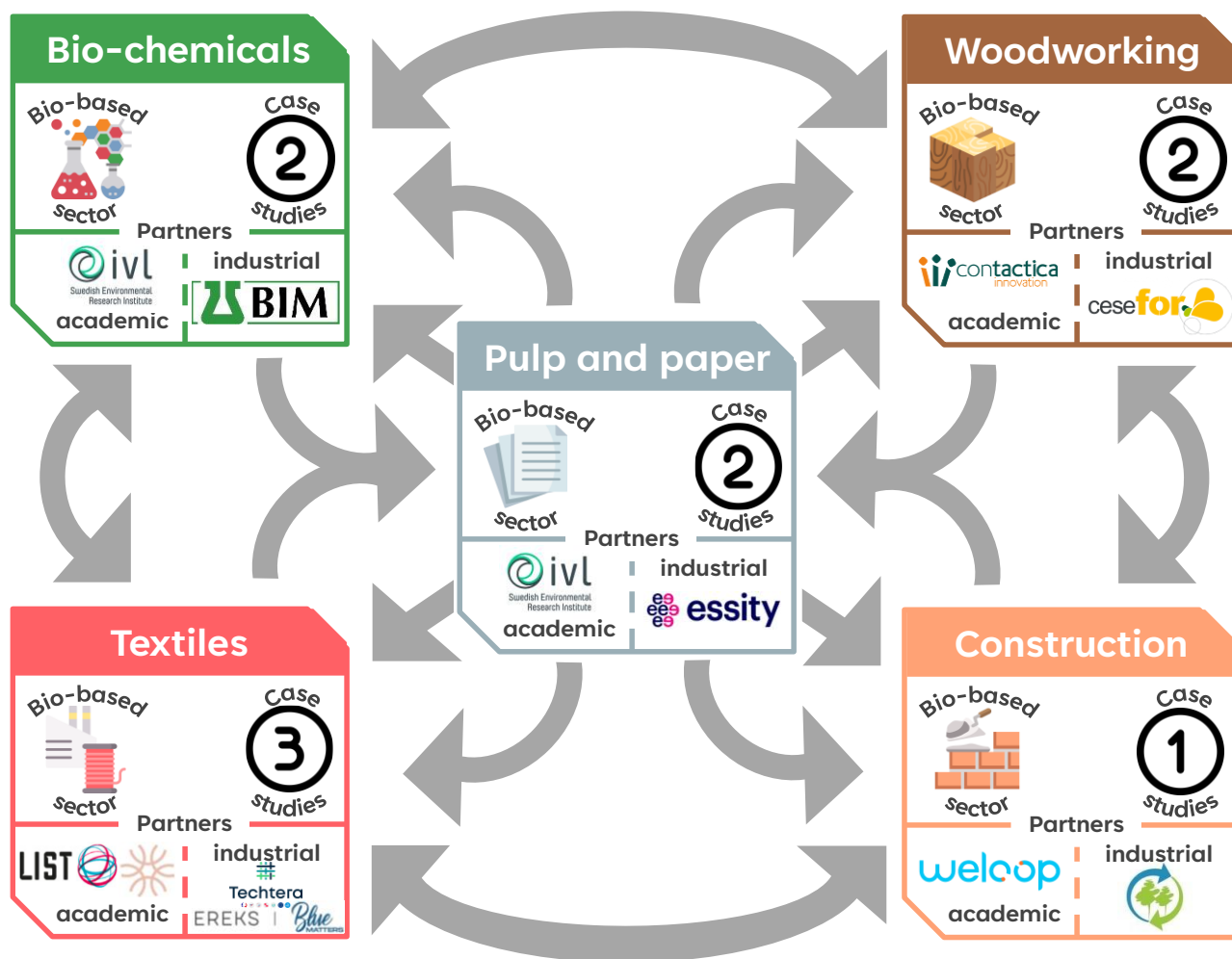


Figure 1. Main features and visualization of the potential interrelationships in terms of sustainability improvement between the 5-target bio-based sectors of the CALIMERO project by means of industrial symbiosis.

1.3 Report structure

The report follows a one-by-one bio-based sector structure, in which potential cross-sectorial solutions are identified for the construction (Section 2.1), textiles (Section 2.2), woodworking (Section 2.3), bio-chemicals (Section 2.4) and pulp and paper (Section 2.5) industries. To conclude, this report delves into these synergies, collecting a general summary of all of them, apart from diving into the future prospects for the 5-target bio-based sectors of the CALIMERO project in Section 3.

2 CROSS-SECTORIAL SOLUTIONS WITH SUSTAINABLE IMPROVEMENT POTENTIAL OF TARGET BIO-BASED SECTORS

2.1 Construction

The global shift toward a CE has highlighted the importance of IS in reducing waste and enhancing material efficiency. Within this framework, bio-based construction materials, such as timber, natural fiber insulation, cellulose composites and bio-resins, present unique opportunities for downstream integration. As these materials reach end-of-life, they can serve as valuable feedstock in other bio-based industries, notably the textiles, woodworking, biochemicals, and pulp and paper sectors.

Bio-based insulation and textile membranes used in construction, including hemp, flax, and recycled cotton, can be redirected into textile applications post-use. Castillo-Rodriguez and Navarro (2023) examined recycled

cotton fibers derived from insulation panels, suggesting their reintegration into textile-grade fibers (Castillo-Rodriguez and Navarro, 2023). Monticelli et al. (2021) proposed for the disassembly and reuse of textile membranes from temporary structures to support textile industry circularity. Genç (2022) noted that natural fiber composites from deconstructed bio-based buildings could be processed into non-woven textile inputs.

In woodworking, the reuse of untreated timber from bio-based construction systems offers significant material value. Kiesnere et al. (2024) emphasized the importance of clean wood recovery from demolition to serve engineered wood sectors. Martins et al. (2023) demonstrated the reuse of dismantled balsa panels in new product development, while other authors validated reclaimed bio-wood in composite boards (Lopes Junior et al., 2023). Additionally, the emergence of prefabricated bio-based construction components offers more uniform and uncontaminated wood waste streams, ideal for reuse in secondary manufacturing. These components often use engineered bio composites which, when disassembled, can be upcycled into new modular elements for furniture production (Kiesnere et al., 2024). This further enhances the interconnection between the construction and woodworking sectors, aligning with circular design principles.

Design-for-deconstruction strategies in bio-based construction also play a pivotal role in enabling high-value recovery of materials. By employing reversible joints and modular systems, buildings can be dismantled without damaging the bio-based elements, preserving their quality for textile or wood sector reuse. These principles are being embedded in emerging building certification schemes, signaling institutional support for cross-sector material reuse. New research also highlights the potential for integrating mycelium-based insulation and acoustic panels, common in modern sustainable buildings, into enzyme production and biotechnology sectors. After use, these fungal composites, rich in chitin and lignocellulose, can serve as substrates for enzyme extraction or be processed into lightweight bio-foams for packaging and filtration (Haneef et al., 2017; Jones et al., 2017). This contributes to a closed-loop system where biological construction materials continue to deliver environmental value in their post-use phase.

End-of-life bio-based construction materials also offer inputs for green chemistry. Lignin-rich timber waste and plant-based insulation can be pyrolyzed or fermented to generate bio-oils and platform chemicals. Luhar et al. (2019) and Kryvenko et al. (2024) explored alkali-activated binders using plant derived ashes from construction, noting their potential in polymer and binder synthesis. Niu et al. (2020) investigated bio-based ash fractions from demolition waste as a resource for phosphorous recovery, reinforcing IS potentials with biochemical applications (Kalmykova and Fedje, 2013). Moreover, advances in biorefineries suggest the feasibility of integrating cellulose rich construction panels and plant-resin residues into biopolymer synthesis (Kryvenko et al., 2024; Luhar and Luhar, 2022). These include applications in bio-based adhesives, sealants, and insulations foams. Such processes transform previously inert demolition waste into functional chemical intermediates, fostering deep symbiosis between the built environment and the chemical industry. Several emerging technologies, such as hydrothermal liquefaction and enzymatic hydrolysis, have shown promise in converting lignocellulosic waste from demolished bio-based buildings into fermentable sugars and bio-crude (Kim et al., 2016). These intermediates can be further refined into solvents, surfactants, and organic acids used in biodegradable detergents and bioplastics. This value chain demonstrates a high-impact reuse route for building components that might otherwise become non-recyclable waste.

On the other hand, biochar derived from slow pyrolysis of wood waste and plant fiber panels from construction demolition can be utilized as a catalyst support or soil amendment in industrial biotech processes (Kamm et al., 2016; Lehmann and Joseph, 2024). This use of biochar enhances the value chain for both the construction and agricultural chemistry sectors, illustrating a multipurpose IS framework that spans materials and energy domains.

New initiatives are exploring the use of fermentation-ready substrates derived from deconstructed building biopolymers, such as polylactic acid and starch-based binders, to produce lactic acid and succinic acid. These

platform chemicals are essential precursors in biodegradable plastics and solvent systems. Integrating construction derived feedstock into biochemical production chains not only diverts organic waste from disposal, but also aligns industrial metabolism with sustainable chemistry objectives (Darkwah et al., 2018; Zhou et al., 2023).

Bio-based construction panels such as cellulose board, strawboard, and cardboard from another IS linkage. Imamura et al. (2018) and Sano et al. (2023) explored recycling techniques for cellulose rich gypsum board paper into fiber applications, relevant for paper-based insulation and packaging. Sarkisov et al. (2024) further noted that combining bio-residue from construction with pulp industry waste yields high-performance insulation, suggesting future hybrid applications. In this regard, there is a growing potential for deconstructed cellulose-based wall panels and acoustic board to be pulped and refined as feedstock in recycled paper production (Imamura et al., 2018; Sano et al., 2023). Regarding pre-sorted and free from synthetic binders, these materials can meet the quality thresholds for tissue paper, molded fiber products, and packaging applications, closing the material loop between the construction and paper sectors. Likewise, synergistic use of waste heat and recovered chemicals from construction processing sites could support energy-intensive pulp recycling operations. Such integration would strengthen the resource and energy loops between the two sectors, creating broader eco-industrial networks. Standardization of input specifications for recycled cellulose from the construction sector could also improve compatibility with existing pulping technologies (Bajpai, 2024; Smook, 2002). Consequently, collaborative efforts between construction and paper industry associations may yield joint guidelines on acceptable levels of lignin, adhesives, and coatings, optimizing cross-sector recycling outcomes.

2.2 Textiles

The textile industry has emerged as a promising sector for IS adoption, representing a relatively recent shift in waste management and resource optimization practices (Neves et al., 2020). While traditional textile manufacturing has long generated substantial waste, the systematic implementation of IS concepts in this sector has gained momentum primarily in the last decade (Castellet-Viciano et al., 2022). This section examines also how the ten key levers identified in the D2.3 (Key levers to improve sectorial and cross-sectorial sustainability) of the CALIMERO project can increase IS within the textile sector and with other bio-based industries.

In this evolving context, various types of waste and by-products, including fabric scraps, fiber waste, and processing residues, are increasingly being recognized as valuable inputs for other industrial processes (Yeşilkaya et al., 2020). Textile materials show potential for circular applications through closed-loop systems and waste valorization approaches. Studies indicate environmental improvements when implementing circular principles, with Schiros et al. (2022) noting that microbial nanocellulose bio textiles achieved lower carbon footprint and reduced carcinogenic impacts compared to conventional textiles. Similarly, Katajainen (2016) found that integrated cellulose processes demonstrated significantly lower water consumption compared to traditional cotton production.

Material exchanges present particularly promising opportunities, as textile waste can be repurposed as raw material input across multiple sectors—construction (for insulation materials), biochemicals (for bio-based products), and pulp and paper industries (Augello et al., 2022; Domenech et al., 2018; Saavedra et al., 2018; Vončina et al., 2018).

Despite its potential, the textile industry faces challenges in implementing IS. Supply fluctuations and material availability are important considerations, as highlighted by Yadav and Majumdar (2024), apart from additional barriers including regulatory frameworks and limited guidance from governing bodies (Herczeg et al., 2018). Likewise, financial constraints and production costs also impact the economic viability of symbiotic

relationships. On the other hand, the heterogeneous nature of textile waste presents technical challenges in material processing, with textile waste composition requiring efficient sorting and processing systems (Piribauer et al., 2020). Geographical factors can also restrict access to available waste resources, emphasizing the importance of proximity to existing industrial facilities.

In essence, the textile industry demonstrates significant cross-sectorial potential for synergies with bio-based sectors. In the construction sector, studies have examined using textile waste in construction materials, particularly for insulation purposes, with researchers like Augello et al. (2022), Giordano et al. (2018) and Salah et al., (2022) highlighting innovative approaches. On that field, one particularly notable example is the use of waste wool to produce thermal and sound insulation materials, as documented by Sbordone et al. (2022). In agriculture, research has investigated the interconnections between textile and agricultural waste, including interesting developments like producing textiles from tomato waste in horticulture, as explored by Lommerse and Loots (2022). The chemical industry has also been a focus of textile waste research, with studies such as those by Vončina et al. (2018) exploring the potential of textile waste as feedstock for chemical production. Additionally, the pulp and paper sector has seen investigations into integrating textile recycling with pulp mills to improve resource efficiency and reduce environmental impact, as documented by Sanchis-Sebastiá et al. (2021). Biotechnology presents another interesting avenue, with research demonstrating the potential of microbial nanocellulose bio-textiles, showcasing innovative applications in textile production (Schiros et al., 2021).

The two case studies of the textile sector addressed in the CALIMERO project demonstrate practical applications of IS. On the one hand, steam generation energy optimization (first case study), plays a relevant role in textile IS networks, where the industry's high energy demands can be partially met through resource sharing and waste-to-energy initiatives (Branca et al., 2021). Mazzoni (2020) reported that implementing shared services and renewable energy in a textile cluster reduced carbon dioxide emissions substantially. Nikolakopoulou et al. (2017) modeled circular economy plants for textiles, showing how energy recovery from textile waste can reduce both environmental impact and operational costs. On the other hand, the development of bio-based alternatives in textile processing (second case study), aligns with studies on bio-based innovations. In this regard, Silva et al. (2022) examined bio-based and bioactive coatings using vegetal waste and by-products, representing an approach to finding sustainable alternatives for conventional textile processing methods. Such innovations can contribute to reduced environmental impact while maintaining product functionality.

Beyond these specific case studies, in the literature conducted it has been identified several alternative applications for textile waste and by-products. As mentioned previously, in the field of building insulation, researchers like Augello et al. (2022) and Giordano et al. (2018) have demonstrated methods of transforming textile waste into insulation materials for construction. Chemical production has also benefited from textile waste, with studies carried out by Vončina et al. (2018) exploring its potential as a feedstock for chemical processes. The pharmaceutical sector presents another innovative avenue, as work by Sorlini and Menato (2020) has investigated using silk waste in pharmaceutical and cosmetic applications. In the automotive and textile industries, Silva et al. (2022b) have developed innovative approaches using leather waste from the automobile industry to create textile coatings. Looking toward sustainable fiber production, Dias et al. (2025) have explored the potential of forest biomass as an alternative source for textile fiber production, offering promising alternatives to synthetic fibers.

Environmental benefits of IS in the textile sector include reduced environmental impacts through mechanical recycling of cotton fibers, as reported by de Oliveira Neto et al. (2022). The same study noted economic advantages through this recycling process. Social implications include potential employment opportunities through new industries focused on textile waste valorization, skill development for circular business models, and health and safety benefits through reduced human toxicity impacts (Dziubaniuk and

Aarikka-Stenroos, 2025; Schiros et al., 2021).

The range of symbiotic relationships identified demonstrates the textile industry's potential to integrate with various sectors to promote sustainability principles. The ongoing integration of CE principles with industrial ecology approaches is strengthening the sector's resilience, enabling it to build and maintain stable symbiotic relationships while optimizing resource utilization across several bio-based industries (Baldassarre et al., 2019; Shi and Li, 2019). Realizing these benefits requires addressing identified challenges through coordinated efforts across regulatory, technological, and market dimensions.

2.3 Woodworking

The woodworking industry has a recurring adoption of the IS concept due to the renewable characteristics of wood, as waste and by-products generated (e.g., sawdust, wood chips or bark) can be used as inputs. Likewise, the energy usually generated during the production process can be coupled with the electricity demand. In fact, this is a common practice that takes place between woodworking companies that focus on the production of sawmill, pellet, particle or fiber board, in addition to plywood. Therefore, a synergetic network of purchase and sale can be established between the by-products generated in the form of waste wood, wood chips, wood dust or fuel wood. On the other hand, in this context it is of paramount importance to take into consideration the fluctuations in the volume of by-products from the producing companies, as these can compromise the raw material availability of the receiving companies. Nevertheless, the woodworking sector has proven to be very resilient to fluctuations in demand in terms of profitability (Daş et al., 2024).

Beyond the provision of material and energy inputs to be used within different woodworking companies, there is room for cross-sectorial synergies within the other 4-target bio-based sectors of the CALIMERO project. In this sense, several examples of IS have been identified, focusing on the case studies addressed in D2.1 (Case studies descriptions and assessment) in relation to the woodworking sector: (i) Laminated Strand Lumber (LSL) production, and (ii) steam production from residual biomass.

The main raw material used in the manufacturing process of the CALIMERO case studies is green wood from Spanish poplar forests, which makes full use of the felled trees. In this sense, the higher quality parts of the trees are used by one company for the production of plywood, while the lower quality parts (usually the upper parts of the trunk) are used by a different company for the production of LSL. Therefore, a part of the raw material, which in other cases is usually discarded because it does not meet certain quality standards required to obtain the final product, is then used as a raw material in another case study to produce a product that will be used in the construction sector (i.e., LSL) (Moradpour et al., 2018).

Similarly, another potential alternative for IS in this case study would be the use of wood fiber as a bio-based insulation material in the residential sector. In this regard, a study conducted a comparability analysis of the material, climate, economic and public health impacts of using wood as insulation versus converting the same amount of wood into pellets to heat the same house in a German context. This evaluation shows that the insulation alternative requires less material over a 4-year period to achieve a given thermal transmittance over the years. In addition, pellet burning produces about 15 times and 100 times higher climate and public health impacts in terms of CO₂ and particulate matter emissions, respectively. Notwithstanding, even with a 70-year time horizon, wood pellets are a better alternative to wood fiber insulation from a cost-effective perspective. This is explained by the fact that today the cost related to the installation process of wood fibers as insulation material is considerable higher compared to the purchase of pellets (Schulte and Jonsson, 2025).

Moreover, several biochemical substances can be produced from organic waste. Adipic acid, typically derived from fossil sources, represents a significant example. Producing adipic acid through bioprocessing routes appears promising because it not only eliminates N₂O emissions, but also enhances the use of renewable

resources, such as biomass, instead of fossil feedstocks. Forest residues, primarily composed of branches and tops from commercial thinning, can be considered a promising renewable resource (Aryapratama and Janssen, 2017).

For the steam production in the plant, which serves as an energy input for the drying and pressing steps, a boiler is fed with waste biomass from previous steps in the LSL manufacturing process. In this sense, wood wastes from the debarking, chipping and screening steps are collected in a silo, although these come also from the last step related to edge trimming and sanding (which have a different composition since they have adhesive traces on them). Consequently, this is an example of using waste as a resource within the same production process. Notwithstanding, the total amount of wood waste collected is not enough to feed the boiler. In this situation, the purchase of external virgin sawdust is required.

Nevertheless, if wood wastes were not needed for energy production, they could be used as a raw material in any of the other bio-based sectors of the CALIMERO project as a combustion input for their respective production processes (i.e., a cross-sectorial solution between the woodworking sector and any other bio-based industry). In this regard, sawdust has proven to have potentialities to be used as input during the pulp production process (i.e., a cross-sectorial solution between the woodworking and the pulp and paper sectors), apart from during the formulation of fertilizers (i.e., a cross-sectorial solution between the woodworking and the bio-chemicals sectors) (Navare et al., 2022). Moreover, if the energy produced during the steam production process is more than enough to supply the plant's electricity requirements, the surplus could be transferred to another industry, thus constituting an additional case of a cross-sectorial solution between the woodworking sector and any other bio-based industry (Patel et al., 2016).

2.4 Bio-chemicals

The bio-chemical sector plays a key role in modern industry, forming the foundation of various bio-based sectors such as construction, textiles, pulp and paper, and woodworking. Given its widespread influence, enhancing resource efficiency within this sector can yield substantial benefits across multiple interconnected industries. One of the most effective approaches to achieving this is by adopting IS, in where the bio-chemical sector can not only reduce resource depletion and minimize its environmental impact, but also foster cost-effective supply chains and enhance cross-sectorial integration.

The necessity of IS in the bio-chemical sector is evident due to its central role in industrial production. Chemicals are fundamental building blocks for nearly every manufacturing process, making them an essential part of CE strategies. By doing so, bio-chemical industries can shift from linear resource consumption models to circular systems where waste streams are transformed into valuable inputs. This shift not only enhances sustainability, but also ensures long-term competitiveness by reducing dependency on virgin raw materials. In this regard, as the demand for bio-based solutions grows, the adoption of IS-based strategies becomes increasingly critical for both the bio-chemical sector and its interconnected industries (Keçi, 2024; Salomone et al., 2020).

A promising approach to enhancing sustainability in ester production as it is also mentioned in D2.1 report (which is doing at Bim Kemi facilities), involves integrating bio-based raw materials through IS. One key opportunity is in replacing fossil-based carboxylic acids with tall oil, a by-product of the pulp and paper industry. Tall oil is obtained during the kraft pulping process, where cellulose fibers are separated from lignin in wood. This complex mixture, rich in fatty acids and resin acids, presents a valuable alternative to fossil-derived chemicals in the esterification process. By utilizing tall oil, the bio-chemical sector not only reduces reliance on non-renewable resources, but also strengthens cross-sectorial collaboration, particularly with the pulp and paper industry. To ensure its suitability for ester production, crude tall oil undergoes refining to remove impurities and optimize its composition. This refined bio-based carboxylic acid can then be directly used in

esterification, aligning with CE principles, while reducing the overall environmental burden associated (Cashman et al., 2016).

Although waste from the pulp and paper sector can be utilized in the bio-chemical industry, the bio-chemical sector can also provide innovative solutions to enhance the sustainability of pulp and paper production. A key cross-sectorial solution between the bio-chemical and pulp and paper industries involves the development of bio-based enzymes to enhance the efficiency and sustainability of pulp and paper production. Traditionally, the industry relies on chemical-intensive processes for pulp bleaching, refining, and deinking, which can lead to high energy consumption and environmental pollution. By integrating bio-based enzymes, such as laccases, xylanases, and cellulases, the pulp and paper sector can achieve more efficient fiber processing, reduce the need for harsh chemicals like chlorine-based bleaching agents, and lower water and energy consumption. Additionally, the bio-chemical sector can provide bio-based coatings and adhesives derived from renewable sources to replace petroleum-based additives in paper production. This synergistic integration improves the environmental footprint and increase sustainable IS between the two industries (Tanveer et al., 2023; Torres et al., 2012).

Another important part of ester production at Bim Kemi is the use of polyethylene glycol (PEG), which is conventionally synthesized through the polymerization of ethylene oxide—a process heavily reliant on fossil-derived ethylene. A sustainable alternative is transitioning to bio-based ethylene oxide, which can be produced from bioethanol derived from various biomass feedstocks. One source of bioethanol could be biowaste from the woodworking industry, which generates significant amounts of residues that can be repurposed for ethanol production. By utilizing these bio-based resources, the production of PEG can significantly reduce dependency on fossil fuels while growing a cross-sectorial synergy between the bio-chemical and woodworking sectors (Soleymani Angili et al., 2021; Zanon-Zotin et al., 2023).

A cross-sectorial solution between the bio-chemical and construction/woodworking industries involves utilizing lignin, a by-product of wood-based construction materials and demolition waste, as a bio-based feedstock for chemical production. Lignin as one component of wood, is often discarded or underutilized in construction waste, despite its potential as a renewable raw material for producing bio-based chemicals like adhesives, and resins. In the bio-chemical sector, lignin can be processed into bio-aromatic compounds, which would be sustainable alternatives to fossil-based chemicals used in coatings, adhesives, and polymers (Razavi et al., 2024; Zhao et al., 2025). Conversely, bio-chemical advancements can support the construction sector by developing bio-based binders and resins derived from lignin, reducing reliance on petroleum-based construction materials. This industrial symbiosis not only enhances waste valorization but also grow a CE in both sectors (Mili et al., 2022).

The increasing volume of textile waste presents a significant environmental challenge, making fabric recycling a crucial solution for sustainability. However, conventional recycling methods often rely on hazardous chemicals, which pose risks to human health and the environment by generation of toxic by-products. A sustainable approach involves integrating bio-based solvents and chemicals into the textile recycling process, creating a cross-sectorial synergy between the bio-chemical and textile industries. For instance, bio-based solvents can be used for dye stripping, eliminating synthetic dyes in an eco-friendly manner, while bio-based chemicals can aid in elastane removal, improving the recyclability of blended fabrics. Additionally, the use of bio-based dopes in fiber regeneration can enhance the production of high-quality recycled textiles without relying on fossil-derived inputs. This cross-sectorial solution reduces the environmental footprint and strengthens the role of bio-based materials in both biochemical and textile sectors (Hammar et al., 2023; Michud et al., 2016).

2.5 Pulp and paper

The pulp and paper sector plays an important role in the economy where it provides essential materials for health and hygiene products, packaging and many other products. These products are key to securing a sustainable lifestyle to people by providing them with essential necessities such as incontinence products, baby diapers and secure packaging materials that prolongs the quality of the products they encase. In terms of CE practices, the industry is known to employ a long sequence of wood processing steps to maximize wood outputs as much as possible per wood inputs.

As mentioned, processing of pulp and paper, regardless of in which process, entails a considerable number of steps, where CE practices are conducted. One key practice is the processing of by-products such as black liquor. It is re-used in the process to help partially fuel the process, instead of wasting the by-product completely. However, there are some waste output flows which are not possible to use as fuel for the process in this way. Abiding by the CE principles, industries should strive to move up to waste hierarchy ladder. In other words, there is a potential to re-use output flows such as generated black liquor rather than to incinerate it for energy.

Another key process is the recycling of the actual products after use. The recycling rate in the packaging sector and the graphic paper sector is already very high. However, recycling of tissue products after use still has a large space for improvement. In this regard, there is a potential for IS implementation across the paper and pulp sector and the other studied sectors in the CALIMERO project. One important non-IS consideration is that the pulp and paper sector is very reliant on the woodworking sector as this sector provides the necessary raw wood material that is required to process paper and pulp. As for potential IS synergies, the waste outputs of the paper and pulp industry have potential IS between the biochemical and construction industry, which will be explored more in depth. In addition, there is also a potential for IS between the pulp and paper industry and the textile industry that will be mentioned.

Black liquor is reused in the pulping process as an energy carrier, where the energy is used in the pulping process to help partially fuel it. However, this results in the destruction of key chemical components which cannot be reused in other systems. Considering this, there is a potential to re-use black liquor in chemical production systems instead of combusting it for energy purposes. This aligns with the waste handling hierarchy, which assigns higher priority to re-use of waste rather than incineration of waste. By applying the waste hierarchy in this manner, it would result in a chemical valorization and a pathway to IS relating the pulp and paper industry to the biochemicals industry. Specifically, a study has shown that the usage of black liquor could be used as an input into the production of porous carbon materials, with examples such as adsorbents, catalyst supports and electrodes. In this case it would be used in emulsification and foaming process (Pola et al., 2022).

In addition, the pulp and paper industry generates large volumes of spent pulping liquors. However, these liquors are rich in lignin-based compounds and have shown potential as alternative binders in the agglomeration of chromite fines. By diverting these liquors from energy into the production of chromite pellets, the industry can not only reduce waste but also displace the use of bentonite, a mined material with fluctuating availability, thus enhancing resource efficiency and circularity across sectors (Pieter le Roux et al., 2024). This represents a potential for IS, where waste streams from the pulp and paper sector become valuable feedstocks for the biochemicals and metallurgical industries. Through this cross-sectorial collaboration, not only are economic and material efficiencies improved, but environmental impacts can also be reduced by lowering fossil energy use and supporting decarbonization strategies in both sectors. The integration of these industries could foster innovation in lignin valorization and stimulate the development of new bio-based industrial applications (Pieter le Roux et al., 2024).

Another waste stream that could be used is the pulp ash that is generated in the combustion processes of

the pulp and paper making. This waste stream needs to be prepared for disposal, where it is usually sent to landfills. However, there is an innovative IS approach that could potentially be applied to this type of waste stream. The study conducted by Ahmad et al. suggests that there is an IS potential between the paper and pulp industry and the construction industry. In the study, the waste ashes generated in the pulping process are used to substitute up to 10% of the material input components that go into concrete production, which would result in an IS effect, where the paper and pulp sector can divert generated ash waste stream from landfills to decarbonizing the construction sector by material substitution of concrete (Ahmad et al., 2023).

However, the authors note that it is important to carry out more research in this area to determine if the physical characteristics of paper pulp ash matches the physical characteristics of the materials that are subject to being replaced by them (Ahmad et al., 2023). This IS potential is also explored in the study by Ruman et al., where wood ash from pulp and paper industries has been studied to replace fossil coal fly ash with renewable wood fly ash, that is generated as a waste output from the pulp and pulp industry (Rumman et al., 2023).

The textile industry sources materials such as cotton or synthetic plastics that both have a considerable environmental impact. However, wood-based inputs, that are essential inputs into the pulp and paper industry, has also started to be used more in the textile industry has seen more usage of wood materials in the production of textile fibers such as lyocell¹. Wood sourcing could potentially lead to environmental impacts such as deforestation. However, the paper and pulp industry have turned to other material inputs such as wheat straw, which is a waste stream generated from wheat harvest².

3 CONCLUSIONS AND FUTURE PROSPECTS

From the findings in the previous sections on the potential for improving sustainability through the IS concept, the following conclusions and future prospects emerge for each of the bio-based sectors addressed:

- For the construction sector, bio-based construction materials such as timber, mycelium composites, cellulose panels, and plant-based binders serve not only as sustainable building components, but also have valuable secondary resources at their end-of-life. Their integration into textiles, woodworking, biochemicals, and pulp and paper sectors illustrates robust potential for cross-sector industrial symbiosis. From mechanical reuse and biopolymer extraction to enzymatic processing and fiber recovery, these materials enable circular pathways that reduce waste, conserve raw materials, and foster innovation across bio-based industries. These findings emphasize the IS is not simply a waste management strategy, but a systemic opportunity to redesign material flows between traditionally separate industries. The case studies reviewed demonstrate that well-characterized, uncontaminated bio-based construction residues can be effectively valorized in downstream processes, supporting product diversification and resource optimization. Realizing the full benefits of IS from bio-based construction waste depends on aligning deconstruction methods, material purity, and logistics to sector-specific feedstock requirements. When such coordination is achieved, it becomes possible to close material loops and enhance circularity across the built environment and the bioeconomy.
- For the textiles sector, the inherent characteristics of textile materials and their significant waste streams facilitate IS both within the sector and with other bio-based industries. The applications within the textile industry range from closed-loop recycling systems to energy optimization through waste-to-energy initiatives. Focusing on the five-target bio-based sectors of the CALIMERO project, textile waste has demonstrated versatility as a valuable resource across multiple industries, including

¹ <https://textileexchange.org/manmade-cellulosics/>

² https://www.essity.com/Images/Factsheet-Wheat%20Straw-Mannheim-ENG_tcm339-123086.pdf

construction (as insulation materials), biochemicals (as feedstock for production), and pulp and paper (as raw material input). The systematic implementation of IS concepts in the textile sector has gained momentum in the last decade, with various types of waste and by-products increasingly recognized as valuable inputs for industrial processes. Studies have quantified significant environmental benefits, including reduced carbon footprints, lower water consumption, and decreased toxicity impacts, alongside economic advantages demonstrated through case studies of mechanical recycling. Consequently, it can be said that the textile industry presents several promising cross-sectoral material and energy synergies in line with the IS concept, though challenges remain regarding supply chain fluctuations, material heterogeneity, and economic viability. The integration of CE principles with industrial ecology approaches continues to strengthen the sector's resilience and ability to maintain stable symbiotic relationships, but further coordination across regulatory, technological, and market dimensions is needed to fully realize these benefits, particularly in addressing the technical challenges of material processing and the financial constraints that may limit implementation.

- For the woodworking sector, the intrinsic properties of both wood and its wastes and by-products obtained during the wood panel manufacturing process have enabled their use in other woodworking companies for multiple purposes. The applications within the woodworking companies range from wood cascading uses such as pellet or plywood manufacturing to energy savings through the use of firewood. Focusing on the five-target bio-based sectors of the CALIMERO project, and for the particular case of the construction sector, it is noteworthy the multi-product perspective of green wood, depending on trunk sections or other types of characteristics such as quality standards. In the same way, the waste from the production of wood panels has been shown to be a useful raw material for other industrial purposes, such as the insulation of houses, the extraction of biochemical substances or for the formulation of biofertilizers, as well as a source for energy production. In this regard, considering the relatively high caloric capacity of wood, some by-products obtained, such as sawdust, entail to be an interesting input to be used during the combustion process, thus obtaining energy outputs (e.g., steam or heat) to be reused in any other industrial sector. Consequently, it can be said that the woodworking industry has several promising cross-sectoral material and energy synergies in line with the IS concept, but priority must be given to those initiatives that aim to use wood by-products or co-products for additional purposes instead of its energetic use. The above is justified by the cascading principle introduced by the EU Renewable Energy Directive (European Commission, 2023). In this regard, the reuse of wood waste, thus prolonging its useful life, is more interesting from an environmental point of view since trees are a sink of CO₂ emissions, so avoiding burning initiatives will avoid returning to the atmosphere this carbon content already sequestered. Nevertheless, from an economic point of view, the latter can be a more feasible solution for investment or logistical reasons, so public incentives could be a good option to reverse this situation.
- For the bio-chemicals sector, this plays a vital role in helping industries become more sustainable—not just by reducing its own environmental impact, but by working closely with others to make smarter use of resources. Through IS, it creates valuable connections with sectors like pulp and paper, construction, woodworking, and textiles. Instead of relying on fossil-based inputs, the bio-chemical industry can turn to bio-based alternatives like tall oil, lignin, and biowaste from other industries. These materials are not just greener, they are often by-products that would otherwise go to waste. Using them helps cut down on emissions, reduce resource depletion, and build more resilient, cost-effective supply chains. But the impact goes beyond swapping out raw materials. The bio-chemical sector also helps its partner industries find cleaner, more efficient ways to operate. For example, esters from the bio-chemical sector are making pulp and paper production less polluting, while natural adhesives made from lignin are helping the construction industry reduce its dependence on petroleum-based products. In the textile world, bio-based chemicals are enabling safer recycling processes that do not rely on harmful substances. What is powerful here is the mutual benefit: the bio-chemical sector

supports others in becoming more sustainable, and in return, it gains new uses for renewable resources. This kind of two-way collaboration is what makes IS so effective, not just as a technical solution, but as a practical, forward-thinking approach to building a more sustainable future for everyone involved.

- For the pulp and paper sector, this plays an important role in creating IS between the sectors in the CALIMERO project. For example, the waste outputs of the pulp and paper industry have potential IS between the biochemical and construction industry such as via black liquor coming out as a by-product of processing which can be used as an input into the production of various materials. In addition, the pulp and paper industry generate large volumes of spent pulping liquors which are rich in lignin-based compounds and could have potential as alternative binders in the agglomeration of chromite fines. This could lead to both reduced waste as well as displacing the use of bentonite, thus enhancing resource efficiency and circularity across sectors. In addition, there is also a potential for IS between the pulp and paper industry and the textile industry, for example via wood-based inputs that has started to be used more in the textile industry, like in the production of textile fibers (e.g., lyocell).

Likewise, based on the study conducted, a list of the identified cross-sectorial solutions is presented in [Table 1](#), highlighting the type of IS, the objective of the link and the sectors involved.

Table 1. Cross-sectorial solutions identified for the 5-target bio-based of the CALIMERO project.

Common synergies			
Type	Description	Examples	
Governance synergies	Sharing of intangible resources such as knowledge, expertise and regulatory frameworks	<ul style="list-style-type: none"> - Unified waste management plan within industrial parks - Cooperative design vision involving industry, academia and users, focusing on developing new products or improving existing ones 	
Shared infrastructure	Pooled use of common infrastructure for improved resource efficiency	<ul style="list-style-type: none"> - Shared material sorting - Shared facilities like meeting rooms, warehouses or processing environments 	
Common services	Collaboration in services that support multiple sectors	<ul style="list-style-type: none"> - Shared use of a truck during the transport process if the raw materials come from the same origin, or are on their way to the final destination - Shared logistics systems for waste collection - Joint research and testing facilities for material quality assessment and verification 	
Sector-dependent synergies			
Type	Case	Sector	Source
Water Water resources are reused to the maximum extent to achieve water saving purposes based on the difference in water quality requirements of different production processes	Reuse of process water for cooling	All	(Ramin et al., 2024)
	Integrated cellulose processes with reduced water consumption	Textiles	(Katajainen, 2016)
Energy Companies are required to improve energy efficiency and optimize energy exchange networks in accordance with overall supply-demand relationships	Use of energy (steam and heat) from wood waste combustion as energy output	Woodworking with others	(Patel et al., 2016)
	Use of black liquor to from the pulp and paper production process as energy output	Pulp and paper with others	(Verma et al., 2019)
	Shared renewable energy services in industrial clusters	All	(Mazzoni, 2020)

Table 2 (cont.). Cross-sectorial solutions identified for the 5-target bio-based of the CALIMERO project.

Sector-dependent synergies			
Type	Case	Sector	Source
Energy Companies are required to improve energy efficiency and optimize energy exchange networks in accordance with overall supply-demand relationships	Waste-to-energy initiatives for textile processing (energy recovery from textile waste)	Textiles with others	(Branca et al., 2021; Mazzoni, 2020)
	Combined heat and power (CHP) plants serving different industries	All	(Hildebrandt et al., 2019)
Material Use by-products or waste generated by upstream production units as raw materials for downstream production	Use of low-quality parts of the green wood as the production of products for the construction sector	Woodworking with construction	(Moradpour et al., 2018)
	Use of wood waste from the production process as insulation material	Woodworking with construction	(Schulte and Jonsson, 2025)
	Conversion of forest residues into biochemicals (e.g., adipic acid)	Woodworking with bio-chemicals	(Aryapratama and Janssen, 2017)
	Use of wood waste from the production process as material input in the pulp production process	Woodworking with pulp and paper	(Navare et al., 2022)
	Use of wood waste from the production process as combustion input	Woodworking with others	(Patel et al., 2016)
	Use of wood waste from the production process as material input in the formulation of bio-fertilizers	Woodworking with bio-chemicals	(Navare et al., 2022)
	Use of wood waste to produce bio-ethanol to be used for polyethylene glycol production	Woodworking with bio-chemicals	(Vallejos et al., 2017)
	Forest biomass for textile fiber production	Woodworking with textiles	(Dias et al., 2025)
	Use of waste wool for thermal and sound insulation	Textiles with construction	(Sbordone et al., 2022)
	Textile waste as chemical feedstock for bio-based products	Textiles with bio-chemicals	(Vončina et al., 2018)

Table 3 (cont.). Cross-sectorial solutions identified for the 5-target bio-based of the CALIMERO project.

Sector-dependent synergies			
Type	Case	Sector	Source
Material Use by-products or waste generated by upstream production units as raw materials for downstream production	Integration of textile recycling in pulp mills	Textiles with pulp and paper	(Sanchis-Sebastiá et al., 2021)
	Use of pulp paper ash to obtain concrete	Pulp and paper with construction	(Ahmad et al., 2023)
	Use of by-product or demolition waste from wood-based products of the construction or woodworking sectors (e.g., lignin) to be used for the production of bio-chemicals (e.g., bio-aromatics like coatings, adhesives and polymers)	Construction/woodworking with bio-chemicals	(Razavi et al., 2024; Zhao et al., 2025)
	Use of lignin (as by-product or demolition waste from wood-based products of the construction or woodworking sectors) to produce bio-based binders and resins for manufacturing wood-based constructions products	Bio-chemicals with construction/woodworking	(Razavi et al., 2024; Zhao et al., 2025)
	Use of textile waste for building insulation	Textiles with construction	(Augello et al., 2022; Giordano et al., 2018; Salah et al., 2022)
	Use of lignin from the kraft process as combustion input	Pulp and paper with others	(Consonni et al., 2009)
	Use of tall oil (a by-product of the pulp and paper sector) to replace fossil-based carboxylic acids in the esterification process	Pulp and paper with bio-chemicals	(Cashman et al., 2016)
	Use of bio-based enzymes (e.g., laccases, xylanases, and cellulases) to improve fiber processing, reducing the need for harsh chemicals, and lower water and energy consumptions	Bio-chemicals with pulp and paper	(Tanveer et al., 2023; Torres et al., 2012)
	Use of black liquor to chemical production (e.g., porous carbon materials like adsorbents, catalyst supports and electrodes for emulsification and foaming processes)	Pulp and paper with bio-chemicals	(Pola et al., 2022)
	Use of lignin from liquors to produce chromite pellets	Pulp and paper with bio-chemicals	(Pieter le Roux et al., 2024)
	Use of wood-based inputs for the pulp and paper industry in the production of textile fibers such as lyocell	Pulp and paper/woodworking with textiles	https://textileexchange.org/manmade-cellulosics/

Table 4 (cont.). Cross-sectorial solutions identified for the 5-target bio-based of the CALIMERO project.

Sector-dependent synergies			
Type	Case	Sector	Source
<p>Material</p> <p>Use by-products or waste generated by upstream production units as raw materials for downstream production</p>	Bio-based fibers for insulation purposes in construction (e.g., hemp, flax or recycled cotton) redirected into textile applications post-use	Construction with textiles	(Castillo-Rodriguez and Navarro, 2023; Genç, 2022; Monticelli et al., 2021)
	Timber from bio-based construction systems can be used in engineered wood sectors in terms of new product development, composite boards or furniture production	Construction with woodworking	(Kiesnere et al., 2024; Lopes Junior et al., 2023; Martins et al., 2023)
	End-of-life bio-based construction materials (e.g., cellulose rich construction panels and plant-resin residues) offer inputs for green chemistry, such as bio-based adhesives, sealants, insulations foams or fermentable sugars and bio-crude	Construction with bio-chemicals	(Kalmykova and Fedje, 2013; Kim et al., 2016; Kryvenko et al., 2024; Luhar and Luhar, 2022)
	Manufacturing of fermentation-ready substrates derived from deconstructed building biopolymers (e.g., polylactic acid and starch-based binders to produce lactic acid and succinic acid)	Construction with bio-chemicals	(Darkwah et al., 2018; Zhou et al., 2023)
	Deconstructed cellulose-based wall panels and acoustic board to be pulped and refined as feedstock in recycled paper production	Construction with pulp and paper	(Imamura et al., 2018; Sano et al., 2023)

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