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Developing strategic supply chain pathways for application of agricultural crops as biobased construction materials, products and modular systems

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Abstract— The construction sector accounts for 37% of global carbon emissions and 40% of EU waste, driving policy initiatives toward decarbonisation and circularity. While biobased materials offer low-carbon alternatives, their limited adoption reflects systemic supply chain barriers rather than technical inadequacy. This research develops and applies a novel hierarchical supply chain mapping framework to identify strategic pathways for agri-crop biobased construction in Ireland, focusing on straw, hemp, and miscanthus. A novel four-stage supply chain mapping framework is developed integrating processing complexity and technological levels, applied in two national stakeholder workshops engaging multiple organisations across agriculture, manufacturing, construction, and policy sectors. Analysis reveals a range of potential supply chains spanning low-technology applications (bales, blown-in insulation) to industrialised products (boards, blocks, modular panels), with processing infrastructure and certification identified as critical bottlenecks. Irish workshops validate straw as the priority pathway, leveraging existing harvesting and chipping infrastructure for immediate market entry via timber-frame and modular systems, with staged expansion toward advanced fibre processing. Hemp presents high-value niche potential contingent on decortication capacity, while miscanthus offers long-term complementary benefits. Cross-cutting enablers include regional processing hubs, accelerated certification, public procurement, and coordinated policy frameworks. The novel hierarchical mapping framework and stakeholder-validated pathways provide a structured roadmap for translating agricultural by-products into viable construction resources, with applicability to similar regional and national contexts.

Keywords— Biobased Construction, Agricultural Crops, Supply Chain Mapping, Strategic Pathways

I. INTRODUCTION

A Research Rational

The construction sector accounts for approximately 37% of global energy and process-related carbon emissions and generates 40% of waste in the European Union (UNEP, 2024; García et al., 2024). In response, the EU has implemented comprehensive policy frameworks including the European Green Deal, Renovation Wave, and Circular Economy Action Plan to drive decarbonisation and circularity transitions (European Commission, 2010, 2020, 2021). Ireland has aligned with these objectives through the Climate Action Plan 2023, targeting 50% emissions reduction by 2030 and net-zero by 2050, alongside a Circular Economy Act (Department of the Environment, 2023; Govt Ireland, 2022).

Biobased construction materials derived from agricultural crops, such as straw, hemp, and miscanthus, offer significant potential for carbon sequestration, reduced embodied energy, and circular resource flows (Churkina et al., 2020; Phan-huy et al., 2023). However, their market penetration remains marginal despite favourable environmental and technical performance characteristics (Le et al., 2024; Parlato & Pezzuolo, 2024). While existing research has extensively characterised material properties, life-cycle impacts, and

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adoption barriers (Affan et al., 2024; Ben-Alon et al., 2021; Chen et al., 2024), the supply chain dimension remains under-studied - specifically how regional supply systems can be strategically developed.

B Research Question

This research examines the potential development of agri-crop biobased construction supply chains in Ireland, focusing on straw, hemp, and miscanthus. The primary research question is: How can Ireland develop viable strategic supply chain pathways for agri-crop biobased construction materials and solutions? Three sub-questions guide the investigation: What barriers prevent mainstreaming of agri-crop biobased construction, and how can these be overcome? What lessons can be drawn from European supply chain development and commercial deployment? What strategic pathways and enabling conditions are most appropriate for the Irish context, given its specific resource base, infrastructure, and market characteristics? Addressing these questions requires integration of European sectoral analysis with context-specific Irish stakeholder engagement and supply chain mapping.

C Paper Outline

This paper reviews biobased construction materials and supply chain barriers, focused on European agri-crop biobased construction solutions and supply chains, applies a hierarchical mapping framework to the Irish context for straw, hemp, and miscanthus, and concludes with discussion and implications for policy, practice, and research. See Figure 1 (Source: Author P. Daly) showing scope and stages of research.

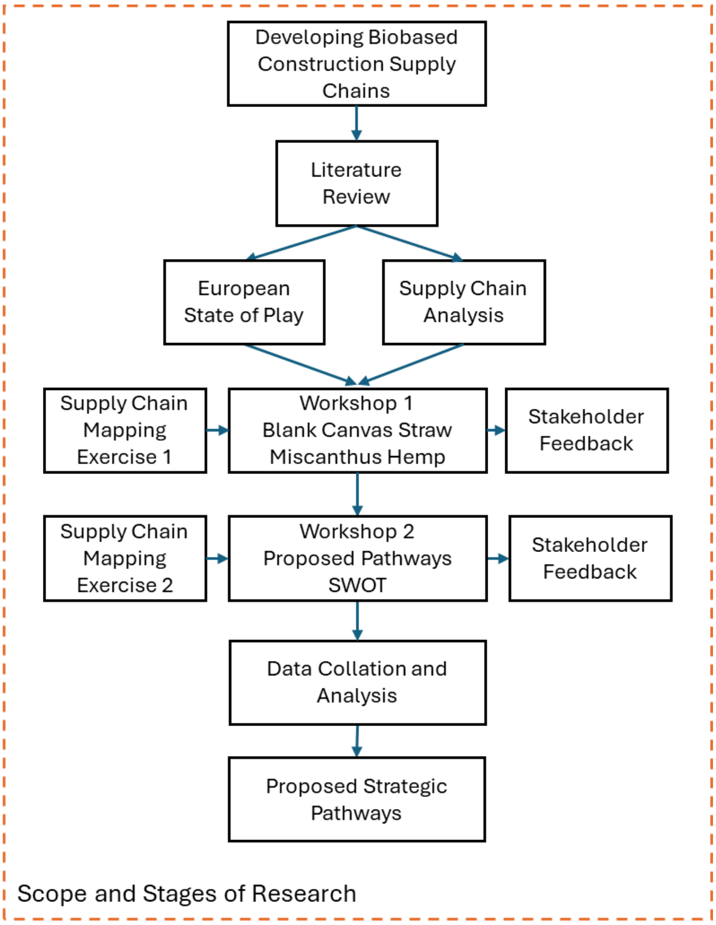


Figure 1 Showing scope and stages of research.

D Research Contribution

This research makes two principal contributions to knowledge and practice: Firstly drawing from precursor empirical analysis of European agri-crop biobased construction supply chains - this research develops a novel hierarchical supply chain mapping framework that integrates four supply chain stages (agriculture, processing, manufacture, construction) with classifications of processing complexity (low, medium, high technology) and product typologies (materials, products, modular systems), enabling systematic analysis and comparison of supply chains. Secondly utilising this mapping / analytical approach it presents stakeholder-validated strategic pathways for Ireland, derived from participatory workshops with multi stakeholder organisations spanning agriculture, processing, manufacturing, construction, and policy sectors. These pathways specify crop priorities, processing infrastructure requirements, technological staging, and policy enablers, providing actionable guidance for industry and government. The methodology and findings offer transferable mapping approaches and finding insights for comparable regional / national contexts across Europe and beyond.

II. LITERATURE REVIEW

A Biobased Construction Materials

Biobased materials, derived from living matter (biomass), whether naturally occurring or synthesised, (Curran, 2010), offer multiple pathways to address sustainability, circularity and decarbonisation challenges. While timber remains the most widely used biobased construction material, agricultural crops including straw, hemp, cork, and miscanthus are increasingly applied across insulation, structural fill, and board applications (Bourbia et al., 2023). These materials demonstrate competitive thermal performance (thermal conductivity 0.038-0.065 W/mK for agricultural crop insulation, comparable to mineral wool at 0.035-0.045 W/mK), superior hygroscopic properties enabling moisture buffering, and high vapour permeability (μ-values of 1-2) that reduces condensation risk (Schiavoni et al., 2016; Affan et al., 2024). Long-term experimental research confirms that properly detailed biobased assemblies maintain thermal performance over 20+ year periods, addressing durability concerns that have historically limited adoption (Korjenic & Teichmann, 2024).

Carbon sequestration and climate benefits represent a critical advantage. Biobased materials sequester atmospheric carbon during growth and, when incorporated into buildings, function as long-term carbon sinks (Churkina et al., 2020). Agricultural crops offer particular advantages: straw insulation achieves combined climate effectiveness of 1,344 kg CO_2eq/t through avoided emissions (930 kg CO_2eq/t versus conventional alternatives) and delayed emissions via temporal carbon storage (881 kg CO_2eq/t) (Phan-huy et al., 2023). Fast-growing annual crops (straw) and perennial crops (miscanthus) enable more rapid carbon integration than slower-growing timber (Cosentino et al., 2025). Comparative life-cycle assessments demonstrate that natural building assemblies (straw bale, hempcrete, earth) consistently outperform conventional alternatives in global warming potential, embodied energy, and resource depletion (Ben-Alon et al., 2021).

Circularity potential further distinguishes biobased materials. Unlike conventional materials ending in landfill or energy-intensive recycling, biobased materials can re-enter biological cycles through composting or controlled biodegradation or serve as bioenergy feedstock with minimal processing (Li et al., 2024), which aligns with circular economy frameworks emphasising cascading use and biological nutrient cycles.

Agricultural crop resources relevant to this study include straw (cereal residue, approximately 270 million tonnes annually from 50.69 million hectares in Europe), industrial hemp (Cannabis sativa L., 28,030 hectares producing 158,150 tonnes in EU-2023, concentrated in France), and miscanthus (perennial grass, approximately 20,000 hectares in EU-2016, though declining in some regions) (European Commission, 2023a, 2023c, 2023d, 2023b; Lewandowski et al., 2016). Ireland's agricultural base is predominantly pastoral (4.5 million hectares grassland, 64% of total land area) with limited tillage (less than 300,000 hectares), which is dominated by straw with minimal niche hemp and miscanthus cultivation (F. and M. Department of Agriculture, 2023; 2022).

B Barriers to Adpotion

Despite favourable environmental and technical characteristics, biobased construction materials remain marginal in mainstream construction. Systematic reviews and empirical studies identify multi-dimensional barriers spanning technical, regulatory, economic, and supply chain domains (Le et al., 2024; Chen et al., 2024; Göswein et al., 2022).

Technical and performance concerns centre on durability, fire safety, and moisture sensitivity. Scepticism persists regarding long-term performance in variable climatic conditions, though evidence demonstrates maintained functionality over 20+ years when properly detailed (Korjenic & Teichmann, 2024; Affan et al., 2024). Fire safety represents a major barrier, particularly for timber and crop-based construction, regarding fire safety requirements and limitations of fire retardants (Markström et al., n.d.; Zerari et al., 2024). Moisture management is critical, as biobased materials require protection from direct water exposure and careful detailing to leverage hygroscopic benefits while avoiding degradation (Amziane & Sonebi, 2016; Koh & Kraniotis, 2020).

Regulatory and institutional barriers include fragmented standards, slow certification processes, and regulatory frameworks / testing regimes geared toward conventional materials. Innovative materials face complexity in certification, with building code restrictions and absence of design guides identified as among the most significant obstacles (Le et al., 2024). Regulatory fragmentation impedes standardisation and market confidence, while lengthy certification processes (e.g., CE marking) add complexity and cost (Le et al., 2023; Zerari et al., 2024). Case studies report recurring difficulties gaining accreditation for materials, hindering project replication and scale-up (Dams et al., 2021).

Economic and market barriers encompass high initial costs, investment risk, and limited qualified labour. Cost and risk-related concerns, including perceived high upfront costs, rank among the three most critical barriers in expert assessments (Le et al., 2024). Market immaturity, lack of raw materials at scale, and absence of financial and regulatory support compound these challenges (Zerari et al., 2024). While some biobased materials reduce embodied carbon and initial production costs, others may not be economically viable across full life-cycle scenarios (Le et al., 2023).

Limited awareness and knowledge among design and construction professionals further impede adoption, with surveys revealing very limited market penetration and identifying information and perception-related barriers as critical obstacles (Chan et al., 2022; Le et al., 2024).

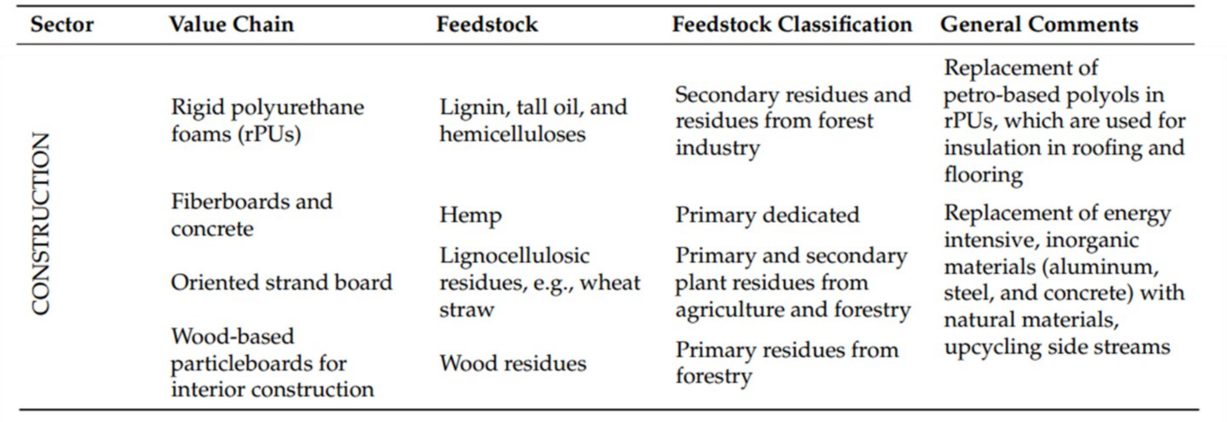
Supply chain barriers include limited availability and inconsistent quality of biobased materials, underdeveloped processing capacity, and fragmented value chains. Case studies document difficulties upscaling production, with constraints from limited availability and heterogeneity in material properties (Dams et al., 2021, 2023; Göswein et al., 2022). Reviews identify fragmented supply chains and material heterogeneity as obstacles to scaling and standardization (Le et al., 2023). The importance of local supply chains is emphasized, yet regional processing infrastructure remains limited (Göswein et al., 2022).

Cross-sectoral competition and land use present additional challenges. Increased biomass demand has implications for biodiversity and water scarcity, with land-use trade-offs arising when valorising biomass for construction versus food, feed, or energy applications (Tripathi et al., 2019; Müller et al., 2015). Systematic reviews of circular bioeconomy transitions highlight sustainability of biomass sourcing as a core barrier, with governance implications of land-use competition requiring careful management (Gottinger et al., 2020).

C Supply Chain Perspectives

While literature on biobased construction material performance and environmental assessment has expanded substantially, explicit analyses from supply chain or value chain perspectives remain comparatively limited. Existing work often draws on broader bioeconomy literature or adjacent sectors (bioenergy, biorefineries), (Cerca et al., 2022; Fernández Ocamica et al., 2025) with construction's distinctive characteristics—project-based production, stringent liability regimes, long service lives, and regionally embedded feedstock systems—only partially addressed Nevertheless, emerging research identifies structural bottlenecks, governance challenges, and opportunities for coordinated development, suggesting that barriers to scaling are systemic rather than solely technical or economic.

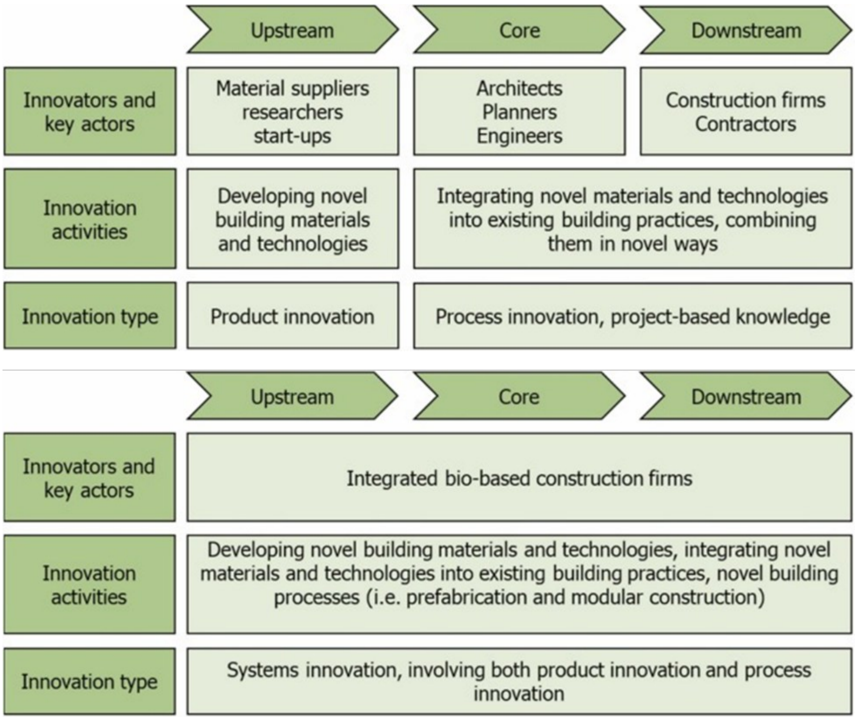
Value chain structures and feedstock types have been systematically mapped by Fernández Ocamica et al. (2025), who identify four distinct construction-related bio-based value chain types: wood-based engineered products, agricultural residue-based materials, hybrid bio-composites, and emerging fast-growing crop systems. Their analysis highlights both the breadth of potential pathways and sustainability-oriented improvement needs, particularly regarding petrochemical-based binders that impede biodegradability and reduce end-of-life circularity. They advocate for greater utilisation of agricultural crop residues, emphasising circular and economic advantages and lower dependence on virgin wood (Fernández Ocamica et al., 2025). See Figure 2 (Fernández Ocamica et al., 2025).



Sector	Value Chain	Feedstock	Feedstock Classification	General Comments
CONSTRUCTION	Rigid polyurethane foams (rPUs)	Lignin, tall oil, and hemicelluloses	Secondary residues and residues from forest industry	Replacement of petro-based polyols in rPUs, which are used for insulation in roofing and flooring
	Fiberboards and concrete	Hemp	Primary dedicated	Replacement of energy intensive, inorganic materials (aluminum, steel, and concrete) with natural materials, upcycling side streams
	Oriented strand board	Lignocellulosic residues, e.g., wheat straw	Primary and secondary plant residues from agriculture and forestry	
	Wood-based particleboards for interior construction	Wood residues	Primary residues from forestry	

Figure 2. Showing four construction value chain types and feedstocks.

Fragmentation and innovation misalignment characterise the sector. Butzin & Rehfeld (2013) argue that transition to biobased construction is complicated by a broad multi-sectoral supply chain with divergent innovation priorities: upstream segments (material development) focus on new bio-based materials or refinements, while core construction segments (design, engineering, planning) pursue innovations in building technologies and processes. These differences in innovation culture and pace create structural misalignments hindering effective knowledge translation and integrated supply chain development (Butzin, 2013). Mazzoni & Losacker (2024) demonstrate that innovation bottlenecks arise from lack of coordination across supply chain segments, each operating under distinct logics, incentives, and organisational structures. They contrast fragmented value chains characterised by non-aligned actors and uncoordinated innovation with integrated models where learning flows, organisational capabilities, and material streams are deliberately synchronised (Mazzoni & Losacker, 2024). See Figure 3 (Mazzoni & Losacker, 2024).



	Upstream	Core	Downstream
Innovators and key actors	Material suppliers researchers start-ups	Architects Planners Engineers	Construction firms Contractors
Innovation activities	Developing novel building materials and technologies	Integrating novel materials and technologies into existing building practices, combining them in novel ways	
Innovation type	Product innovation	Process innovation, project-based knowledge	

	Upstream	Core	Downstream
Innovators and key actors	Integrated bio-based construction firms		
Innovation activities	Developing novel building materials and technologies, integrating novel materials and technologies into existing building practices, novel building processes (i.e. prefabrication and modular construction)		
Innovation type	Systems innovation, involving both product innovation and process innovation		

Figure 3. Supply chain mapping of biobased construction sector, with Upper - non-aligned actors and non-integration of innovation actions and Bottom - suggested model of fully integrated actors, activities and types.

Feedstock logistics and supply present significant challenges. Seasonal harvesting patterns necessitate storage infrastructure or flexible year-round processing capacity. Doubling storage duration from 3 to 6 months can increase total straw supply costs by approximately 20% (Karras & Thrän, 2024) while unfavourable weather conditions reducing available working days can raise costs by up to 13% (Wang et al., 2022). Moisture management is critical, with material quality and durability associated with moisture content of approximately 20% (w.b.) during preprocessing (Jackson, 2015). Transportation represents a major and variable cost component, with costs highly dependent on distance, density, and preprocessing state. Regional straw supply costs in Germany increased by circa 85% depending on location and storage duration (Karras & Thrän, 2024) while Chinese case studies found expanding transportation distances could increase delivered straw costs by up to 53% (Wang et al., 2022). Economic transport radius for low-density agricultural biomass is typically short, with Spanish case studies finding baling became economically preferred at delivery distances above 11-16 km (Suardi et al., 2019). Densification through pelletisation or panel manufacture enables longer-distance transport but requires capital investment in preprocessing infrastructure (Ebadian et al., 2021; Jackson, 2015).

Regional processing infrastructure and capacity gaps represent major bottlenecks. Limited availability of commercial hemp fibre processing and decortication equipment has been identified in multiple markets (Mark et al., 2020; Khanal & Shah, 2024) Economically feasible conversion scales for herbaceous feedstocks tend to be relatively large, resulting in too few suitably-sized processing facilities for regional supply chains Quality testing infrastructure is unevenly distributed, constraining ability to verify thermal, mechanical, and hygrothermal performance at scale. These infrastructural limitations reinforce fragmentation and create coordination challenges: processors are reluctant to invest without guaranteed feedstock supply and market demand, while farmers and builders hesitate to commit without reliable processing capacity (van den Oever et al., 2023).

Standardisation, certification, and evidence gaps persist. The absence of standardised testing frameworks, long-term performance data, and digital traceability tools constrains architect, engineer, and procurement confidence (Le et al., 2023; Chen et al., 2024). Natural materials exhibit greater variability than industrially manufactured products, resulting in batch-to-batch performance differences that complicate specification and liability management. Recommended supply chain interventions include standardised cultivation protocols, grading systems, blending strategies, statistical quality control, and end-to-end traceability (García-Velásquez et al., 2022). Standardisation must extend beyond product performance to include harmonised life-cycle assessment methodologies, environmental product declarations, and end-of-life classifications (Le et al., 2023).

Coordinated sectoral initiatives offer promising models. The Building Balance initiative in the Netherlands established several regional agri-crop-based construction supply chains through long-term partnerships between growers and housing associations. By committing to multi-year deployment of biobased materials in social housing, the initiative created demand certainty and reduced risk for growers, processors, and installers. They also developed novel supply chain mapping and visualisation tools supporting multi-stakeholder planning. Although execution gaps (overreliance on informal agreements) reduced trust among some growers, the approach demonstrates feasibility of coordinated regional supply chain development with potential replicability (Suzan Vandongen, 2024). See Figure 4. Source - Building Balance.

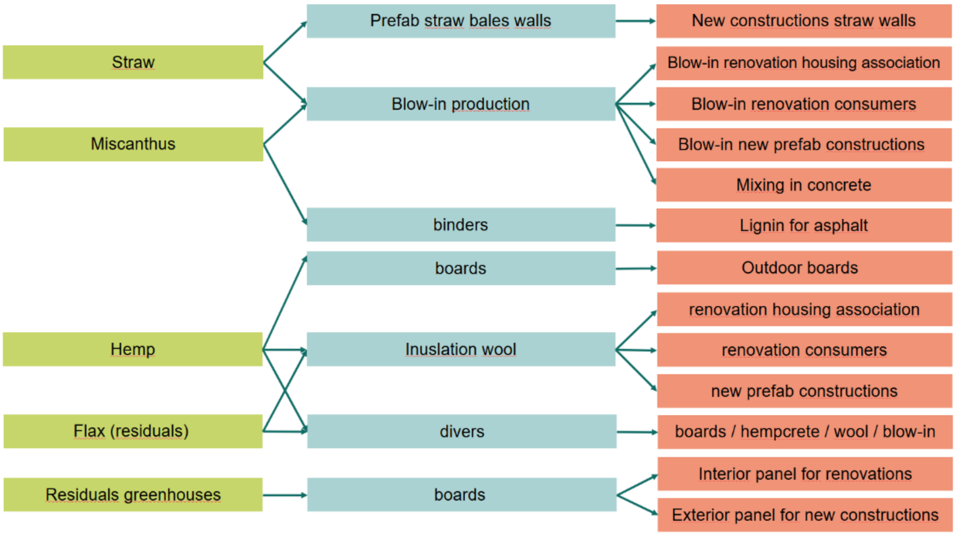


Figure 4. Showing potential agri crop supply chain pathways in Netherlands

D European State of Play and Supply Chains

Despite barriers and supply chain challenges, an emerging range of biobased construction solutions and supply chains are active across Europe. A significant examination of agri-crop biobased supply chains in Europe was undertaken by Daly and Barill 2024, which informs this research. A comprehensive survey of European commercial agri-crop biobased construction solutions was undertaken as well as an examination of 13 supply chains (6 in detail). 57 companies were identified and analysed across Europe, comprising 46 engaged in materials and products manufacturing and 15 focused on modular construction systems, as follows; (Daly & Barril (2024a).

Materials and Products: Analysis revealed that hemp-based enterprises represent the largest group, concentrated in Western Europe (particularly France, Germany, and Benelux regions) proximate to significant hemp cultivation and established processing infrastructure. Straw-based manufacturers (excluding direct farm-supply of bales) are more geographically dispersed, particularly in Eastern Europe. Products span a technological spectrum from low-technology solutions (straw bales, blown-in straw) through medium-technology products (boards, batts, quilts, non-load-bearing blocks) to high-technology applications involving advanced processing to extract cellulose, lignin, and fibres for industrial applications. Hemp-focused companies primarily manufacture hempcrete for timber infill and masonry blocks, alongside diverse medium-technology products including boards, batts, and quilts. Miscanthus-based products remain minimal, with only one board product identified. Most solutions are non-load-bearing materials applied in timber-framed construction, encompassing both wet systems (hempcrete cast in situ or in prefabricated modules) and dry systems (boards, batts, blown-in insulation). See Figure 5 (Daly & Barril, 2024a), which summarises application types across broad technology-complexity levels by resource type.

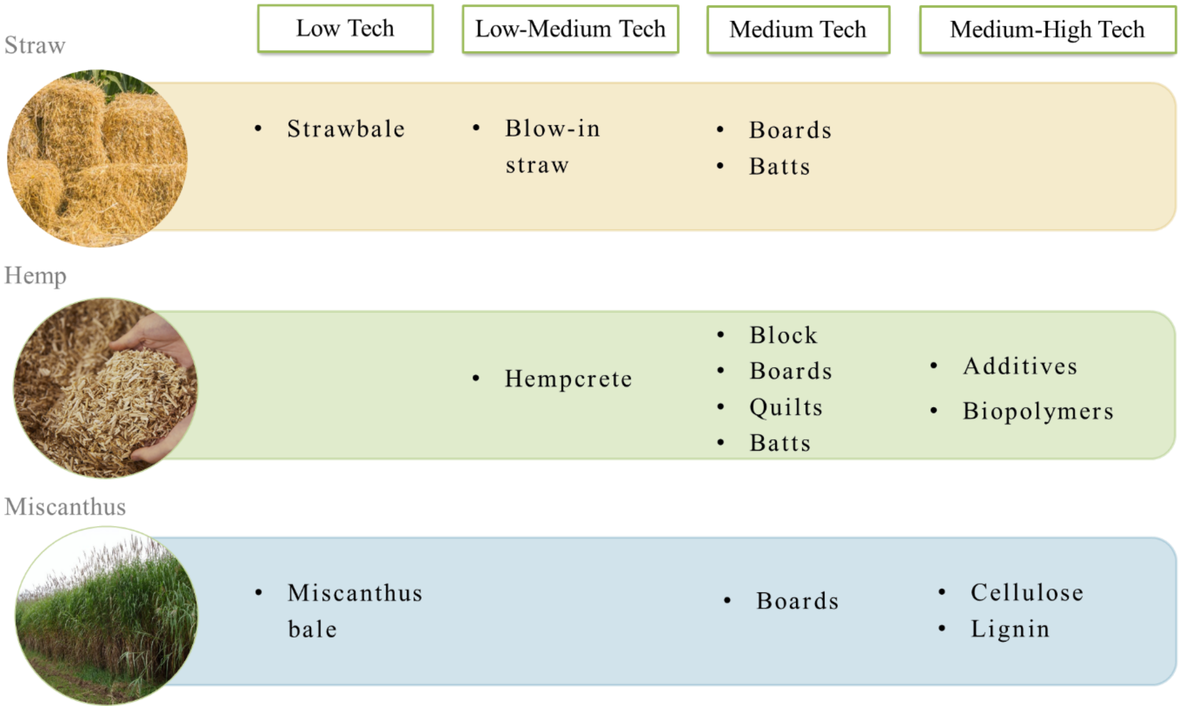
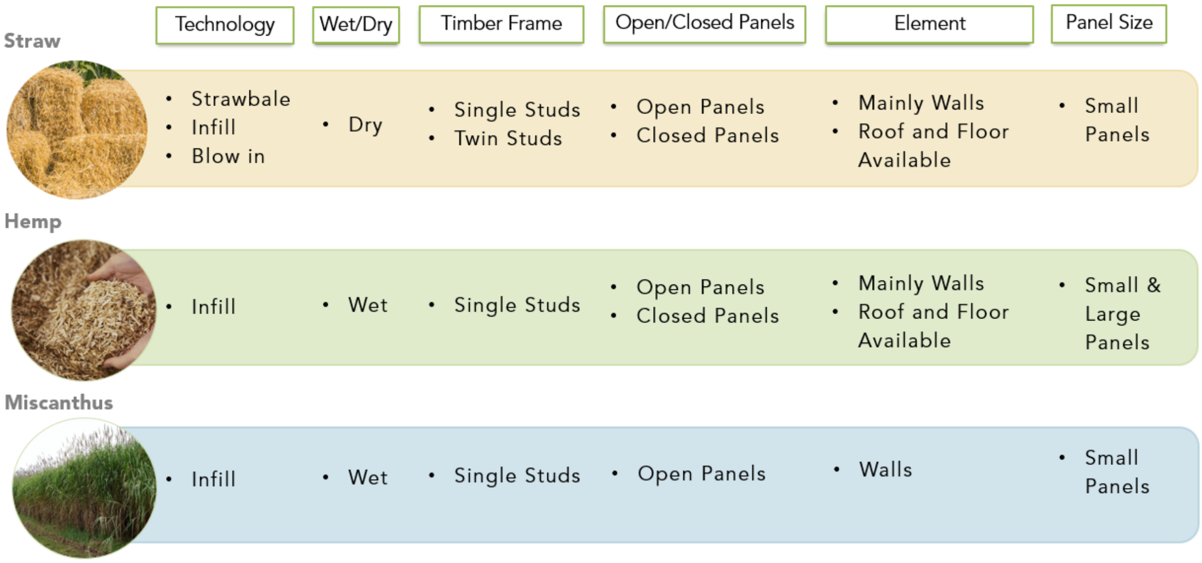


Figure 5. Presents a summary chart of the type of application of agri-crop biobased materials and products under broad technology – complexity levels.

Modular Systems: Fifteen companies specialised in modular construction systems utilising agricultural crops, with several operating across Europe and expanding production capacity. Straw emerged as the most prominent resource, followed by hemp and one miscanthus example. Straw-based panels are predominantly dry systems for walls and roofs, incorporating compressed bales or chopped loose straw via blown-in methods within twin-stud structural frames. Panel dimensions vary widely, in both open and closed configurations, primarily for new buildings with some retrofit applications. Hemp-based modular panels typically employ wet systems with drying times dependent on components and build-ups, are generally larger, use single-stud frames, and are available in open and closed formats for new construction. The miscanthus system identified aligned closely with hemp-based typologies. See Figure 6 (Daly & Barril, 2024a).



	Technology	Wet/Dry	Timber Frame	Open/Closed Panels	Element	Panel Size
Straw	Strawbale Infill Blow in	Dry	Single Studs Twin Studs	Open Panels Closed Panels	Mainly Walls Roof and Floor Available	Small Panels
Hemp	Infill	Wet	Single Studs	Open Panels Closed Panels	Mainly Walls Roof and Floor Available	Small & Large Panels
Miscanthus	Infill	Wet	Single Studs	Open Panels	Walls	Small Panels

Figure 6. Provides a summary chart of the main characteristics of the modular panel system per resource type.

This European landscape demonstrates an emerging sector with diverse technological approaches, resource utilisation, and market strategies. While straw benefits from established harvesting and processing infrastructure, hemp dominates in manufactured products due to developed decortication capacity in key regions. The prevalence of timber-frame integration and growing modular system adoption indicate potential pathways for standardisation and scaling.

Supply Chain Case Studies: Additional case analysis of 13 representative producers (6 with detailed interviews / site visits) examined operational supply chain dynamics to understand how European biobased construction supply chains function in practice. Cases were selected to represent diversity across crops (straw, hemp, miscanthus), products (materials, products, modular systems), processing complexity levels, and geographic distribution. A meso-level supply chain mapping framework was developed analysing four key stages—agriculture, processing, manufacture, and construction—with cross-cutting dimensions of transport/storage and regulatory/market context. Figure 7 (Daly & Barril, 2024b) illustrates a representative case: a wet-process hempcrete modular wall panel manufacturer located adjacent to a hemp processor, operating in a well-developed national hemp industry with construction sub sector, with established quality standards and certification, highlighting advantages of resource-processor proximity and challenges of wet material drying in assembly-line production.

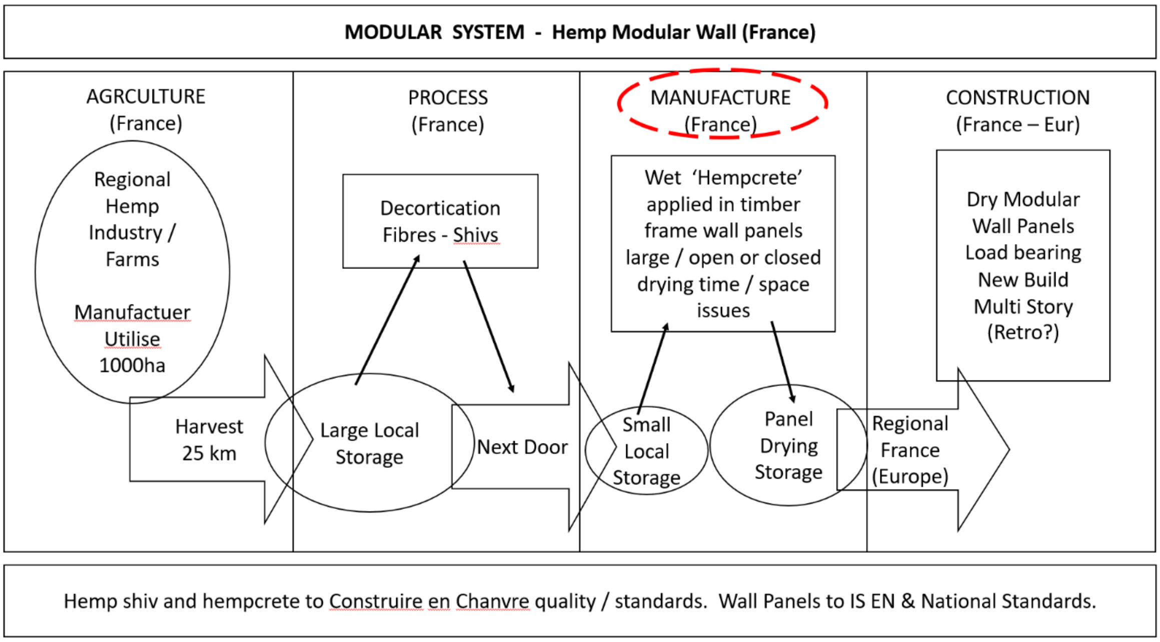


Figure 7. Presenting case example high-level supply chain mapping of this wet process hempcrete based modular wall panel manufacturer located adjacent to processor and seeking to develop several regional factories.

Table 1 (Daly & Barril, 2024b) presents an overview of the 13 companies showing supply chain stage focus, input resources, product outputs, and key characteristics. Blue – miscanthus, Yellow – straw, Green – hemp.

COMPANY TYPE	INPUT	OUTPUT			SUPPLY CHAIN STAGES			
	Resource	Material	Product	Modular Panel	Agriculture	Process	Manufacturer	Construction
Processor*	Miscanthus	Cellulose and lignin				Extraction of key elements - 50% Cellulose, 25% Hemi cellulose, 20% Lignin, 2% Phenols.	Supply to third party manufacturers. Developing possible cellulose insulation product.	Lignin used in tarmac.
Grower & Processor*	Miscanthus	Miscanthus chips in different sizes and fibres			170ha (20ha own area +150ha external contract). Regional resource withing 100 km of processing plant	Specialist processor supply multiple sectors and industries, using range of varietes and processing techniques. Processing performance 150m3/h.	Supply to diverse range of sectors and industries. Clients include several biobased construction product manufactures.	Blow in straw, blocks, boards, panels etc.
Grower & Processor*	Straw	Straw Chips, Straw Pellets, Straw Crumb			Currently 4,000ha (25,000 straw tonnes) 1,000ha own + 3,000ha local farmers)	Processing straw for animal bedding (chips and pellets) - milled, dedusted (5mm sieve), treated with a bactericide and mould inhibitor.		
Grower, Processor & Manufacturer*	Straw		Building straw bales & Blow in straw chips, Certification Service		Straw used circa 1000ha from local farmers	Customized straw re-baling or chopped and milled for blow in insulative infill.	Supply bales and blow-in straw under an ETA, and also provide on-site consultancy services to certify local resources.	Straw bale and blow in straw chip infill in timber frame.
Manufacturer*	Straw		Blow in straw fiber, Boards & batts		Straw supplied from circa 30-40km radius (year contract)	Fragmentation and Defibration process through a patent wet technology to produce straw fibres.	Manufacturing blow in straw fibre (ETA) and a range of boards and batt straw insulations with CE marking.	Straw fibre, boards and bats for timber frame construction.
Manufacturer*	Hemp and other crops		Wall board & Plasters		Inputs from crop by-products, fibrous waste from various sources, and recycled material.	At the moment UK hemp provider is supplying the resources.	Small production of 7 to 10,000 sqm/year of carbon sequestering plasterboard, currently using hemp. The technology has been designed to be used with any kind of crop.	Carbon sequestering plasterboard.
Manufacturer (Construction)*	Hemp		Hempcrete, boards, block & batts		French Hemp	Hemp sourced from French industrial processor (+900km)	Line of hemp based products, hempcrete infill (hemp, lime plus addition of probiotics to speed up carbonation process) and hempcrete masonry blocks.	Hempcrete infill to timber frame and hempcrete masonry blocks.
Manufacturer*	Hemp		Hemp Block, Boards & Batts	Dry Panel System			Manufactured off-site composite hemp panels make up the superstructure, delivering a weathertight building on-site. Manufactured Hemp Blocks, Boards and Batts.	
Manufacturer (Construction)*	Hemp		*In development - Hemp Blocks and Boards*	Wet & Dry Panel System	UK / French sources	Annual capacity inputs: 200tonnes of hemp shiv (1/3 UK Processed rest Processed France), 1,800 m3 of flexible fibre, 56,000 timber panels.	Structural modular wall panels interlocking / DfD enabled, composed from a patent hemp composite and fibre insulation & panel internal partition variation.	It can be used up to 3 stories without additional structure, 60kg each panel - ease of handling and assisted non powered lifting.
Manufacturer (Construction)*	Hemp			Wet Panel System	Utilises circa 1000ha hemp per year, supplied from 25km radius	The decortication process occurs next to the manufacturing panel, providing a large-scale supply that is stored in a silo on as need basis.	Structural wall panels of hempcrete in single stud frame. 8-72h horizontally drying time + another 21 days drying time before shipment. Production capacity 30 panels/week.	Open or Closed panel ready for on-site assembly-crane required. 2 types of panels, load-bearing up to 3 floors, non-loadbearing up to 28m with additional timber structure.
Manufacturer (Construction)*	Straw			Dry Panel System	Resources from 10-30km radius. seeking to promote carbon/regenerative farming	The farmers deliver directly to their storage facilities at winter for 1 -2 years storage / drying. In house processing - de baling, cutting, cleaning etc.	2 factories (Lithuania 2008,22 people - semi automated, 1 shift, 12,000sqm per year) (Slovakia 2024, 5people + Fully Automated ,2shifts, 60,000sqm per year).	Small open panels - directly to site for installation or to local assembly factory halls with local companies (Holland, Denmark, Finland, Sweden) to create larger / closed panels.
Manufacturer (Construction)*	Straw			Blow in Straw Chips Panel System		Third party processor supplies de-dusted chopped straw ready for blow in insulation about 6% moisture control. 15km.	Modular structural wall panel in single study open panel - closed / finished on site. Panel weight around 60kg/sqm-crane required.	Timber frame walls - can be used up to 3 stories, with additional timber structure up to 5 stories.
Manufacturer (Construction)*	Straw			Dry Panel System	Straw from local regional farms		Manufacturing Load Bearing Prefab Straw Bale panels system in 'Flying' - temporary local Factories.	Rapid one day structural build. Crane required.

Table 1. Presenting an overview of a representative sample of biobased construction companies who undertook semi structured interviews, showing; supply chain stage, input resource type, product output (material, product or modular system) and supply chain stages / commentary. *Showing representative companies for more detailed case study.

Key insights from the case study analysis include the following:

Agricultural Resources: Straw is the most abundant and widely available feedstock, though hemp and miscanthus are actively utilised. Manufacturers obtain raw materials through varied arrangements from open-market purchases to contract growing, with some cultivating crops for trials. While many prioritise regional sourcing, others transport feedstocks over long distances to secure consistent supply and quality. Storage practices differ - some rely on farmers to hold material until collection, while others manage large-scale storage directly.

Processing: Processing complexity ranges from basic (direct bale use) to highly specialised (decortication, fiberisation). Straw is sometimes used directly but may be re-baled, chipped, filtered, or refined into fibres for blown-in insulation, boards, or batts. Hemp requires advanced decortication to separate fibre and shiv - fibres are used in quilts and composites, while shiv underpins hempcrete and block manufacture. Hemp processing is often undertaken by independent specialist plants, while straw processing is more commonly integrated within manufacturing operations. Processing location varies from cultivation areas to inter-regional and cross-border trade (e.g., French hemp shiv exported to UK and Italy).

Manufacturing and Construction: Manufacturing strategies differ by product type. Bulk materials and standard products are made for stock, while modular systems are usually produced to order. Straw is predominantly farm-baled, though some firms re-bale or chip to specified standards, or compress into modular systems or press fibres into boards. Hemp shiv is used in hempcrete blocks and infill with proprietary lime-based binders, while fibres are processed into quilts and batts. Modular systems are manufactured on production lines similar to timber-frame assembly. Products are used in diverse applications, with strong uptake in timber-frame systems and growing interest in modular wall panels, primarily for new-build markets with emerging retrofit opportunities.

Critical Bottlenecks Identified: Processing infrastructure gaps (particularly hemp decortication), certification and testing requirements, transport costs and logistics for low-density materials, moisture management and storage capacity, and regulatory variations across markets emerged as consistent challenges. Despite shared characteristics, supply chains display significant diversity in resource choice, processing, manufacturing methods, standardisation levels, logistics, and market strategies.

E Literature Findings

Agri-crop biobased construction materials—primarily straw, hemp, and miscanthus—demonstrate substantial environmental, technical, and socio-economic benefits. Life-cycle and field studies confirm low embodied carbon, biogenic carbon storage, competitive thermal and hygrothermal performance, and long-term durability, positioning these materials as viable substitutes for conventional, carbon-intensive construction solutions. They also offer rural development potential through farm diversification and local supply opportunities.

Commercial and supply chain evidence across Europe indicates that the sector is emerging but unevenly developed. Hemp-based manufacturers cluster in regions with established decortication infrastructure, while straw-based products are more widely dispersed, reflecting local agricultural availability. Miscanthus remains marginal. Most applications are non-load-bearing, typically integrated within timber-frame construction, with modular wall panels increasingly employed to enhance quality, repeatability, and scaling potential. Across 13 representative European supply chains, key operational challenges include processing infrastructure gaps, seasonal feedstock availability, moisture-sensitive storage, transport costs for low-density materials, certification requirements, and regulatory fragmentation. These systemic factors, rather than material inadequacy, largely constrain adoption.

In conclusion, biobased construction materials are technically viable and commercially emerging, but their wider adoption depends on addressing systemic barriers through integrated supply chain development, regional infrastructure planning, and stakeholder coordination. Research and policy interventions targeting these structural constraints are essential to realise their potential as scalable, low-carbon construction solutions, particularly in smaller or less-developed markets.

This research addresses these gaps by: i) developing a hierarchical supply chain mapping framework integrating processing complexity and technological stages, ii) applying this framework to examine Irish development potential, and iii) engaging multi-stakeholder participation to identify strategic pathways suited to smaller-economy contexts.

III. RESEARCH METHODS

This research employs a pragmatic qualitative inquiry framed within an exploratory case study methodology (Yin, 2018) using mixed methods to examine biobased construction supply chain development. Ireland is treated as a critical case of a smaller EU economy with strong climate policy alignment but constrained processing infrastructure, enabling analytical generalisation to comparable contexts (Eisenhardt & Graebner, 2007). The study integrates the following methodological components.

A Literature Review

To establish a contextual foundation for this study, a structured narrative literature review was undertaken over late (Oct to Dec) 2025, on a representative corpus of peer reviewed publications, synthesising research on biobased construction materials, adoption barriers, with a focus on supply chain perspectives.

The PRISMA framework (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guided the search, selection, and data collation process., supporting systematic planning, execution, and transparent reporting of reviews and meta-analyses, enhancing methodological rigor and reproducibility (Moher et al., 2009; Page et al., 2021). A conventional Research Design Flow was undertaken as follows:

The online literature search was conducted systematically across three major academic databases to ensure breadth and coverage of relevant peer-reviewed scholarship. Scopus and Web of Science provided access to quality academic data basis with Google Scholar providing wider material reach including grey literature.

Search strategies combined keywords using Boolean operators (AND, OR) with keywords including "biobased construction," "agricultural crops," "straw," "hemp," "miscanthus," "supply chain," "barriers," and "circular economy." The search was supplemented with some traditional chain referencing.

Inclusion criteria were based on English language peer-reviewed journal articles published primarily between 2015 and 2025 and supportive relevant policy and technical documents / reports.

Preliminary screening involved title and abstract review, identifying relevancy of work, followed by second text analysis and finally data extraction from most relevant literature.

B Hierarchical Supply Chain Mapping Framework

A precursor European biobased construction state of play and supply chain case analysis, utilised a meso level mapping identifying key supply chain actors, resources, activities, outputs, and issues across a four stage division of the supply chain, representing each key sub sector - agriculture, processing, manufacture and construction - with transport and storage being a feature across all four stages, and market and regulatory issues being important contextual factors, see Figure 8 (Daly & Barril, 2024a, 2024b).

Based on same a novel hierarchical framework was developed integrating the four supply chain stages, with i) processing complexity levels (low/medium/high technology), ii) product typologies (materials/products/systems), and iii) cross-cutting factors (transport, storage, regulation, markets). This framework was piloted within multi stakeholder workshops and enabled systematic comparison and critique of supply chain configurations and identification of bottlenecks, investment requirements, and strategic opportunities.

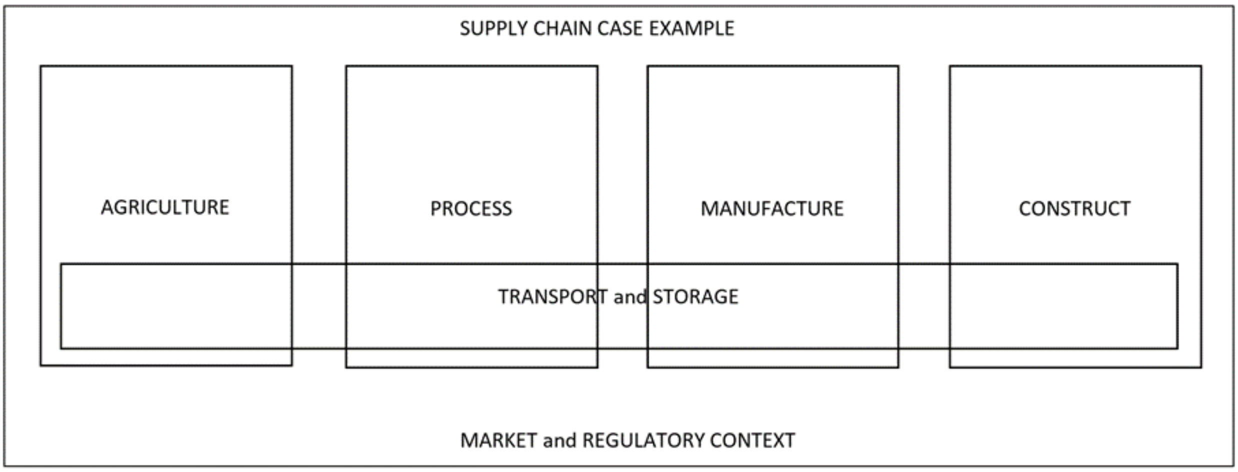


Figure 8. Showing schematic of scope and categories of high-level supply chain mapping exercise conducted in this research across four key supply chain stages, agriculture, process, manufacture and construction.

C Irish Stakeholder Workshops

A National Supply Chain Development Working Group representing multiple stakeholder organisations (state, NGO, commercial, research) spanning agriculture, processing, manufacturing and construction sectors was recruited from a stakeholder network of key government Departments, agencies, NGOs, representative bodies and commercial actors engaged in the bioeconomy / biobased materials sectors. The group of circa 20 organisations and individuals participated in two national Irish workshops to examine how Ireland could promote and develop agri-crop biobased construction supply chains.

Workshop 1 (September 2024) combined seminar presentations on European state of play and supply chain analysis findings with participatory mapping exercises of possible supply chains and issues, recorded using blank supply chain canvas templates, which were based on the meso level framework map in Figure 1. Three focus groups (hemp, straw/miscanthus, modular systems) identified key actors, technological requirements, logistics challenges, barriers, certification pathways, and market drivers. Stakeholder feedback was collated by group leader notation, canvas mapping notes and online questionnaire conducted at the session.

Workshop 2 (January 2025) presented proposed conceptual supply chain maps for each crop (developed from Workshop 1 and European analysis) for structured evaluation, using prompt question guide to focus group discussions, with canvas mapping of proposed supply chains. Three focus groups conducted SWOT analysis of crop-specific pathways using standardised question frameworks. Stakeholder feedback was collated by group leader notes and canvas mapping notes, and SWOT canvas notes.

Workshop data was compiled in a workshop report and thematically analysed to identify recurring themes, priorities, barriers, and opportunities. Resulting strategic pathway development integrated European case insights with Irish stakeholder input to specify crop priorities, processing infrastructure requirements, technological staging, and policy enablers for straw, hemp, and miscanthus.

D Supply Chain Mapping Framework

Building upon European case analysis, a novel hierarchical supply chain mapping framework was developed and applied to enable systematic comparison of supply chain configurations, identification of bottlenecks, investment requirements, and strategic opportunities. The framework integrates four principal dimensions:

Dimension 1: Supply Chain Stages (Horizontal Axis) Four sequential stages structure the supply chain incorporating;

- Agriculture: Crop cultivation, harvesting methods, primary storage requirements;
- Processing: Transformation activities including chipping (Level 1 - low complexity), re-baling and filtering (Level 2 - medium complexity), and decortication/fiberization (Level 3 - high complexity);
- Manufacture: Product assembly, curing, quality control spanning materials (loose-fill, chips, shives, fibres) → products (boards, batts, quilts, blocks) → systems (modular panels, prefabricated assemblies);
- Construction: Application methods, integration with building systems (timber-frame, masonry, modular), installation requirements.

Dimension 2: Processing Complexity Levels (Vertical Hierarchy) Three technological levels differentiate processing intensity, capital requirements, and operational costs:

- Level 1 (Low): Conventional agricultural methods (baling, basic chipping) utilizing standard farm equipment;
- Level 2 (Medium): Specialised processing (re-baling to specifications, filtering, compression, basic boards) requiring dedicated equipment;
- Level 3 (High): Advanced industrial processing (decortication, fiberisation, engineered products with binders) demanding significant capital investment and technical expertise

Dimension 3: Product Typologies (Output Classification) Three product categories reflect increasing manufacturing complexity and market value:

- Materials: Loose-fill insulation, chips, shives, fibres for direct application;
- Products: Manufactured items including boards, batts, quilts, blocks requiring processing and assembly;
- Systems: Integrated modular panels and prefabricated assemblies combining materials, structural elements, and finishes.

Dimension 4: Cross-Cutting Factors Contextual dimensions affecting all supply chain stages:

- Transport and storage requirements (seasonal availability, moisture management, logistics costs);
- Regulatory and certification pathways (testing standards, building codes, quality assurance);
- Market and demand characteristics (regional vs. pan-European, new-build vs. retrofit, procurement mechanisms).

Application Methodology: The framework was deployed in Irish stakeholder workshops to facilitate participatory pathway identification and evaluation. This enabled visual mapping and analysis of supply chain pathways showing crop-specific routes from agriculture through processing levels to product types and construction applications. By overlaying cross-cutting factors, the framework identifies critical decision points, investment thresholds, and enabling conditions for supply chain development. This tool was developed in three iterations as it was deployed in stakeholder workshops.

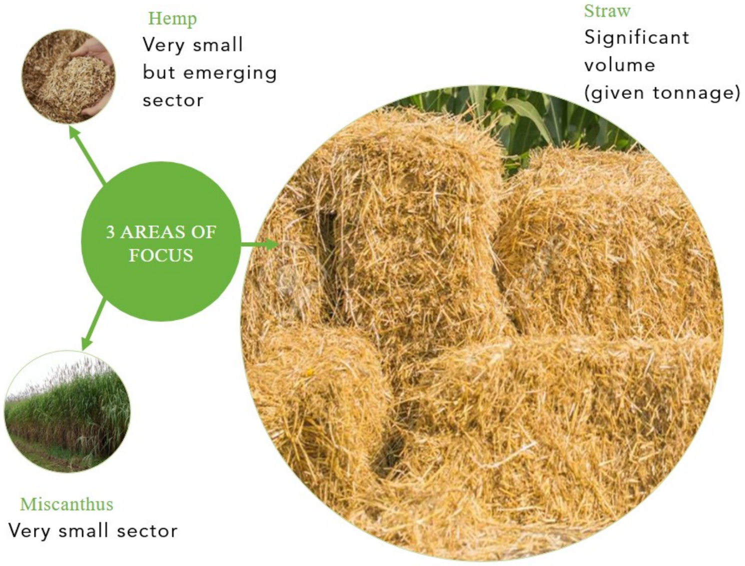
E Methodological Limitations

This exploratory qualitative case study limits statistical generalisability, with findings intended for analytical transferability only. The narrative literature review and purposive stakeholder workshops may introduce selection, interpretive, and group-dynamic biases. The supply chain mapping framework relies on qualitative judgement rather than quantitative metrics, constraining comparability and outcome precision.

IV. RESULTS - IRISH SUPPLY CHAIN DEVELOPMENT

A Irish Resource Context

Ireland's agricultural base is predominantly pastoral, dominated by grassland (4.5 million hectares, 64% of total land area) and livestock production, with tillage and cereal cultivation representing less than 300,000 hectares compared to continental European countries (Department of Agriculture, 2023; Department of Agriculture, 2022).This context creates distinct opportunities and constraints for agri-crop biobased construction supply chain development. See Figure 9 (Daly & Barril, 2024a).



STRAW	260,300 Ha 2020
MISCANTHUS	593 Ha 2020
HEMP	72 Ha 2022

Figure 9. Showing graphic summary of Irish agri-crop resources for straw, hemp, miscanthus.

Straw represents the largest resource, at over 250,000 hectares, a food by-product with conventional harvesting infrastructure and established chip processing capacity (five processors nationally). This existing infrastructure positions straw as the most accessible low-technology supply chain pathway, enabling direct application of straw chip as blown-in insulative infill in timber-frame and modular construction, with potential for staged expansion toward advanced fibre processing and manufactured products.

Miscanthus, a perennial crop with lower operational and carbon costs, a niche crop below 600 hectares, faces barriers of failed prior bioenergy initiatives (hundreds of hectares removed) and limited current cultivation. However, its similarity to straw in harvesting and processing presents potential if planting scale can be established.

Hemp represents a niche industrial crop below 75 hectares with specialist harvesting requirements (retting), equipment and advanced processing needs (decortication), neither of which exist in Ireland. Despite this major infrastructure gap, established continental hemp-lime construction methods have generated latent Irish interest, with various case examples existing.

B Synthesis Mapping and Workshop Approach

To facilitate stakeholder understanding of supply chain dynamics and support participatory pathway identification, a synthesis mapping was developed integrating European findings with the hierarchical framework (Section 3.3). This visual tool presents the biobased construction supply chain across four key stages (agriculture, processing, manufacture, construction), processing technology levels (1-3), manufacturing complexity (materials → products → systems), and construction applications (primarily timber-framed). Each crop's distinctive characteristics, processing requirements, and potential pathways were mapped, creating a dynamic presentation framework for stakeholder engagement.

See Figure 10 (Daly and Barril, 2024b) showing tiered conceptual framework for mapping biobased construction supply chains with circularity feedback – utilised in Irish supply chain development workshops.

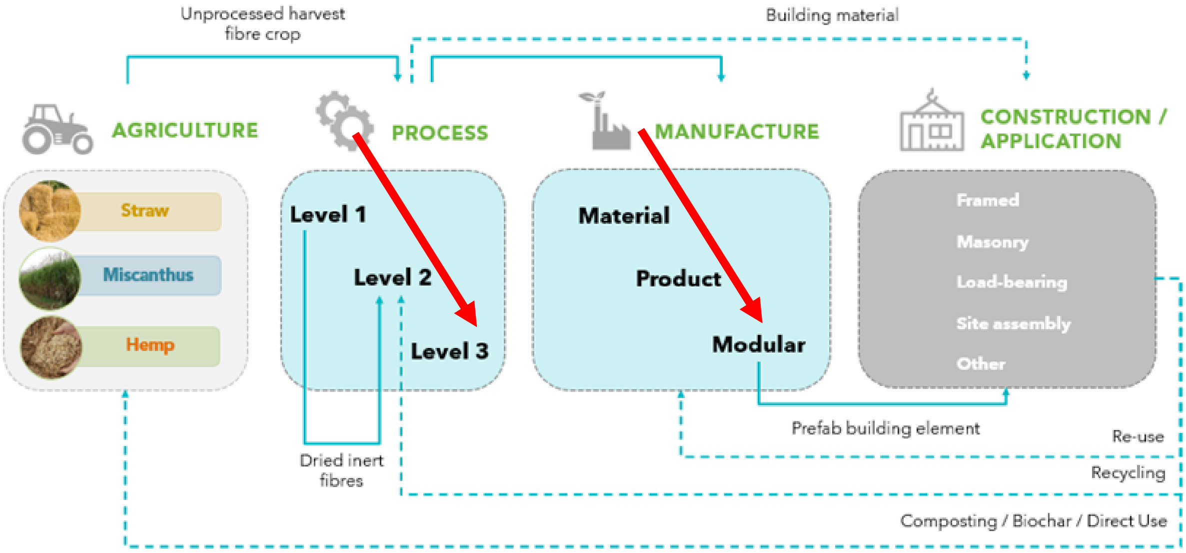


Figure 10 Showing development of conceptual mapping for biobased supply chains.

C Strategic Principles for Irish Application

Synthesis of European commercial solutions and supply chain case studies yielded five strategic principles informing the Irish supply chain development:

Principle 1: Build on Existing Resources and Infrastructure Successful European supply chains leverage established agricultural practices and processing capacity. France's hemp construction sector benefits from existing hemp cultivation and decortication infrastructure, while straw-based solutions across Europe utilise wide scale resources and conventional harvesting / processing equipment. For Ireland, this suggests prioritising crops and processes aligned with existing agricultural and processing assets.

Principle 2: Prioritize Low-Technology Entry Points - European evidence demonstrates that low-technology solutions (bales, blown-in insulation, basic chips) enable rapid market entry with minimal capital investment, creating demand and confidence before progressing to advanced products. The Netherlands' Building Balance initiative exemplifies this staged approach, beginning with straw bale and blown-in applications before expanding to manufactured products.

Principle 3: Stage Technological Progression - Supply chain development should follow a staged pathway: low-technology direct applications → medium-technology products (boards, batts) → high-technology engineered solutions. Each stage builds processing capacity, market acceptance, and investment confidence for subsequent advancement.

Principle 4: Develop Combined Material-Product-System Pathways - Successful companies integrate across multiple product types and applications rather than single-product focus. This diversification spreads risk, serves varied market segments, and maximises resource utilisation.

Principle 5: Integrate with Timber-Frame and Modular Construction - European uptake concentrates in timber-frame systems and modular construction, sectors experiencing growth and offering standardisation opportunities. Irish pathway development should target integration with these expanding construction methods.

These principles, combined with the hierarchical mapping framework, provided the foundation for Irish supply chain pathway identification and stakeholder engagement.

D Workshop 1: Critiguing Potential Supply Chains in Ireland

The first national workshop brought together stakeholders to identify practical routes for establishing agri-crop biobased construction value chains in Ireland. Following presentation of European research findings and synthesis mapping, participants divided into three focus groups (hemp, straw/miscanthus, modular systems) for participatory mapping exercises using blank supply chain canvas templates.

Hemp Value Chain: Hemp was viewed as a promising but niche industrial crop for Ireland. A promoter start-up reported potential yields of four tonnes per acre with licensing not considered a major constraint. However, moisture control during harvest remains critical (construction-grade fibre requires <15% moisture), particularly in Irish wet climate. Processing infrastructure emerged as the principal gap: decortication plants require investments ranging from approximately €250,000 for small second-hand equipment to €3-5 million for larger modern facilities. Post-processing, fibre values can rise from €250 to €1,500 per tonne. Manufacturing hemp quilt or batt insulation or block products would require additional manufacturing investment, while lack of certification continue to impede adoption. Despite challenges, hemp's high-quality fibre has cross-sectoral potential beyond construction. The group concluded that hemp should be developed primarily as a broad industrial crop with niche bioconstruction application of shiv material, contingent on processing capacity and certification frameworks.

Straw and Miscanthus Value Chains: Miscanthus was recognized as a low-input, long-lived crop well suited to Irish conditions, complementing straw through staggered harvest seasons. Straw offers the most immediate opportunity due to existing agricultural and processing infrastructure. Both crops would require localised fibre-processing capacity for manufacture of insulative batts or quilts, with wet-processing systems for board manufacture being energy-intensive and costly. Establishing regional processing hubs near growers was identified as essential to reduce transport and energy burdens. Product innovation in straw-based rigid panels and blow-in insulation is advancing in Europe, but Irish market uptake is constrained by certification, fire safety, and binder costs for some products. Participants emphasised that supply-side investment should follow demand activation. Straw, as the largest Irish agri-crop resource and food by-product, provides an immediate low-tech entry route to biobased construction with significant scaling potential.

Modular Systems and Integrated Approaches: The modular systems group explored integrating agri-crop materials into prefabricated construction. Participants recommended a regional cooperative model similar to the Netherlands' Building Balance initiative and proposed a National Biomaterials Plan to coordinate crop selection, pilot manufacturing, and policy alignment. Diversifying feedstocks beyond the three primary crops to include flax, willow, and rush was seen as essential for resilience. Modular manufacturers could serve as early adopters through regionally distributed pilot plants, each requiring investment of potentially €2-5 million. Design for disassembly and reuse should be prioritised to embed circularity from the outset.

Cross-Cutting Enablers: Across all groups, participants identified shared priorities: local processing capacity, material certification and testing, and demand creation through public procurement (particularly social housing, schools, heritage renovation). Policy mechanisms including the Corporate Sustainability Reporting Directive (CSRD) and Environmental, Social, and Governance (ESG) criteria were noted as emerging market drivers. Establishment of carbon credit methodologies could add further value to supply chains.

E Strategic Supply Chain Pathways

Building upon Workshop 1 insights and European strategic principles (Section 3.4), detailed supply chain pathway mappings were developed for each crop, applying the hierarchical framework to specify processing levels, product types, and construction applications.

Straw Pathways: Straw was identified as having highest potential given established resource base (~250,000 hectares), status as food by-product, and existing primary processing (chipping) facilities nationally. Priority Pathway S1 leverages straw chip as blown-in insulative infill, with regulatory certification already achieved by several European companies. This presents the quickest, lowest-tech, lowest-investment supply chain pathway in Ireland, with potential applications in expanding timber-frame (S1a) and modular system (S1b) sectors. From this initial pathway, further innovation and expansion could be facilitated: Pathway S2 utilises quality-controlled straw bales in construction, dependent on improved harvesting, baling, and storage protocols. Pathway S1c advances to manufactured boards of various densities, requiring innovation in bio-binders and additional manufacturing investment. Pathway S3 involves fiberisation of straw chips, enabling either direct use as insulative infill in timber-frame (S3a) or modular systems (S3c), or further manufacture of insulative boards, batts (S3b), or quilt insulation. This staged progression from low-tech direct application to advanced fiber-based products provides a strategic roadmap for supply chain development, as seen in Figure 11 (Source: Author Daly P.).

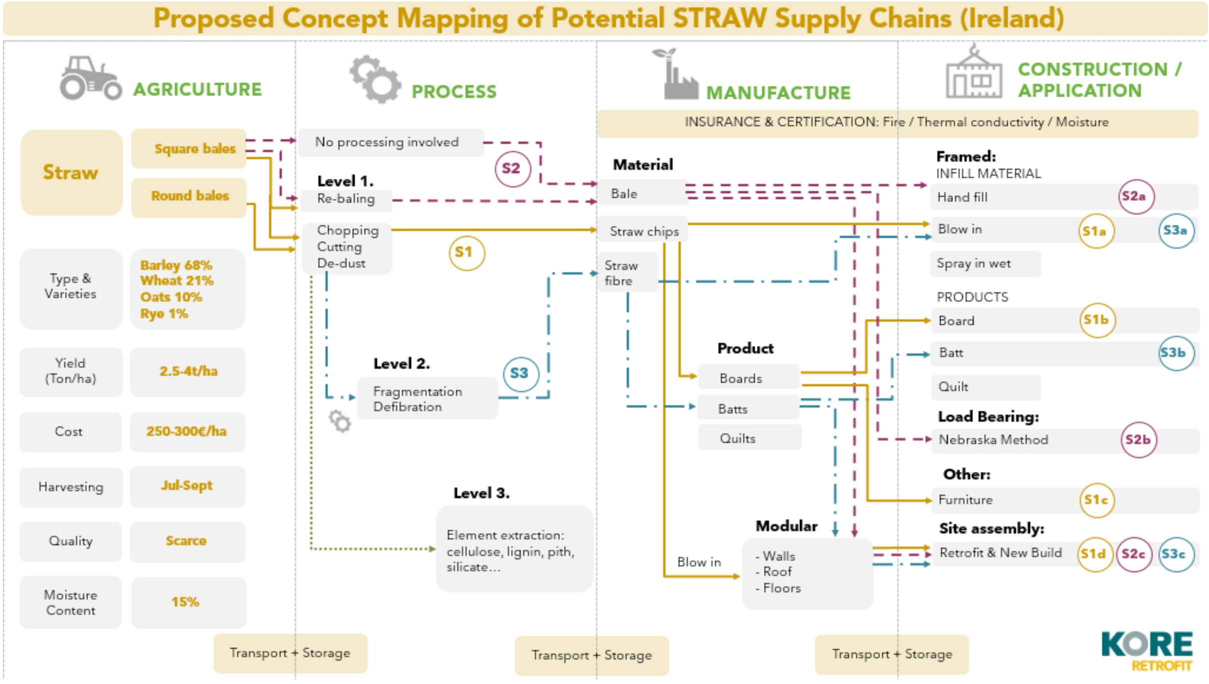


Figure 11. Showing strategic supply chain pathways for Straw biobased construction solutions.

Miscanthus Pathways: Miscanthus, being a perennial crop with lower operational environmental impact and carbon costs, has similar technical potential to straw. Pathway M1 involves chipping for insulative infill or construction boards. Pathway M2 pursues fiberisation for application as insulative infill or in manufacture of construction products (boards, batts, quilts). However, all pathways are contingent on expansive planting and quality control at harvesting. The crop's environmental credentials (carbon capture, soil remediation, marginal land suitability) present long-term advantages, but prior bioenergy market failures and high establishment costs create farmer reluctance. Strategic development would require guaranteed markets, potentially through long-term procurement commitments or ecosystem service payments, seen in Figure 12 (Source: Author Daly P.).

Hemp Pathways: Hemp faces a critical bottleneck in the absence of industrial-scale decortication for separation of shivs and fiber. If decortication infrastructure could be established (estimated €500,000 for single decorticator, up to €10 million for regional network), Pathway H1 would utilise shiv as insulative infill, either dry or as wet-fill bio-composite (hempcrete). Pathway H2 would process fiber into quilt insulation, though fiber may be economically better allocated to higher-value applications in textiles or plastics reinforcement given processing costs and value. Stakeholder feedback indicated significant farmer interest in contract growing if supply chain demand were established, and latent market interest exists due to

European hemp construction precedents. Development would require cooperative ownership models, long-term licensing reforms, government grant support, and clear certification pathways, as shown in Figure 13 (Source: Author Daly P.).

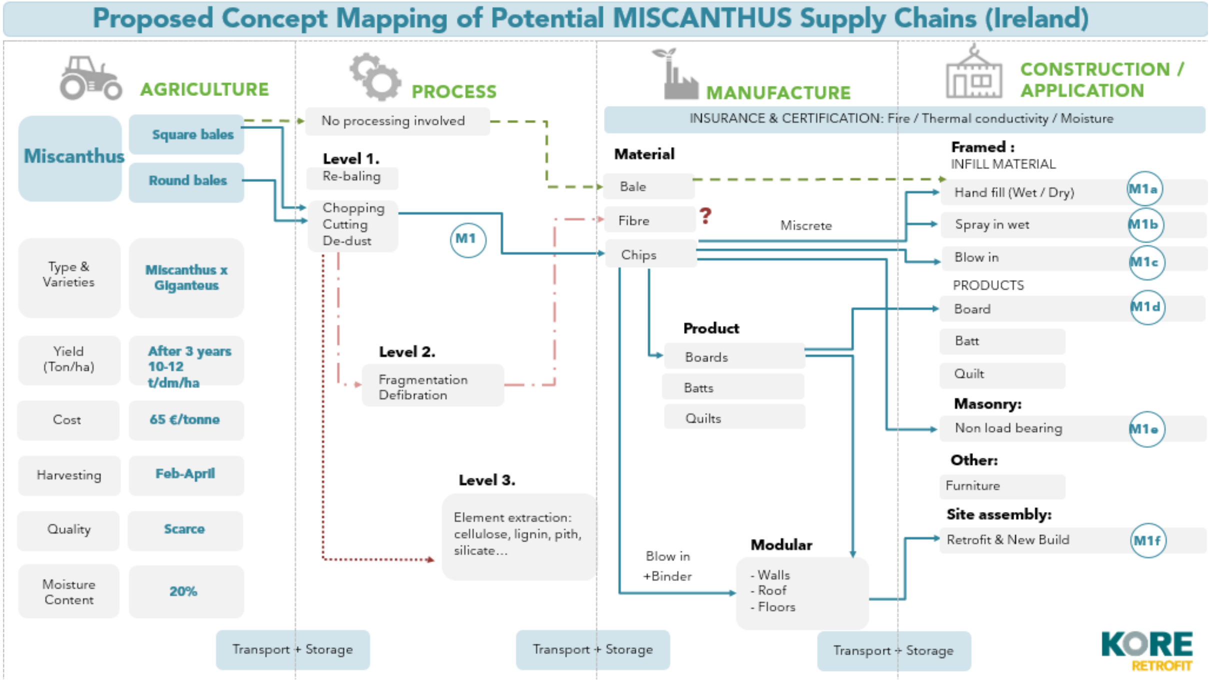


Figure 12. Showing supply chain mapping for Miscanthus in Ireland.

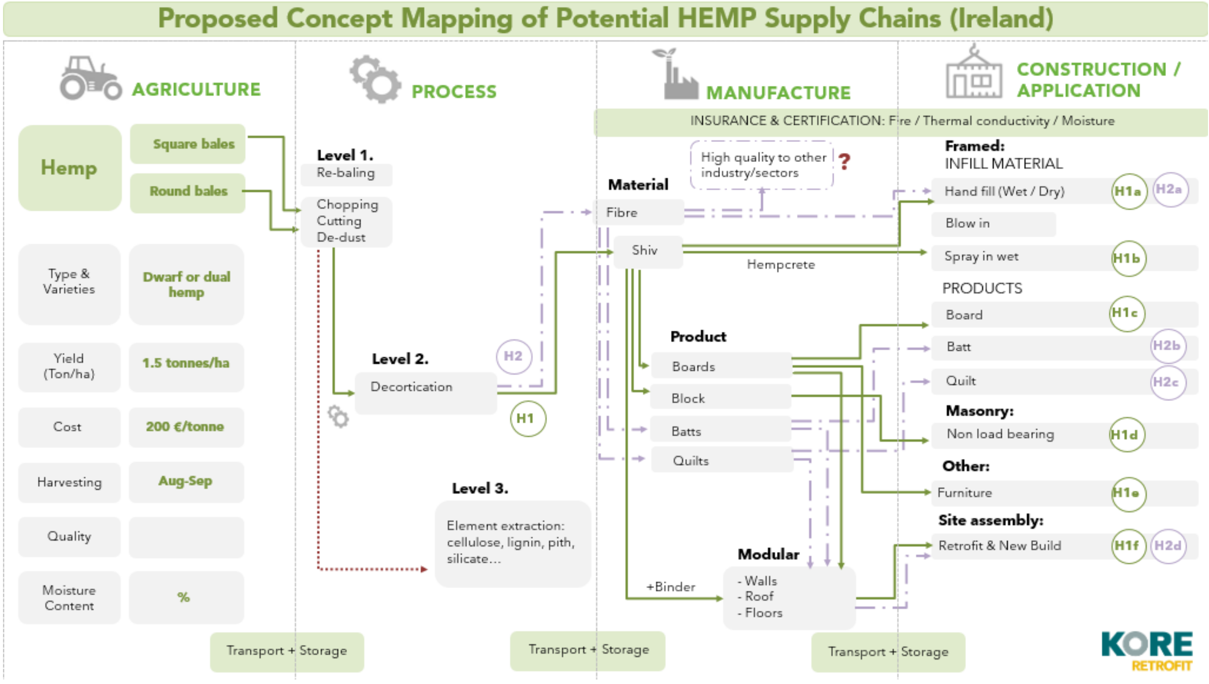


Figure 13. Showing potential hemp supply chain pathways.

Generic Supply Chain Aspects: All pathways require resolution of transport and storage challenges (capital costs, moisture management) and comprehensive regulatory testing toward material and product certification (estimated €70,000 per product, lengthy timelines).

F Workshop 2: Pathway Evaluation

The second workshop presented the detailed supply chain pathway mappings (Figures 11-13) for stakeholder evaluation through structured SWOT analysis, validating and refining the proposed pathways.

Straw SWOT: Stakeholders confirmed straw's immediate potential for insulation products but identified supply variability (weather-dependent, regionally concentrated in eastern counties), capital requirements (€300,000 estimated for existing chip processing infrastructure, €1-2 million for fiber-processing plant, €70,000 for certification), and market barriers (insurance, regulatory compliance, consumer perception). Potential applications in modern methods of construction (MMC), new-build housing, and retrofitting align with existing woodchip material uses. Financial incentives, training programmes, and public procurement policies were emphasised as critical enablers for early adoption. Performance requirements include thermal conductivity of 0.040 W/mK, fire resistance, and controlled moisture content.

Miscanthus SWOT: Discussion reflected limited confidence due to prior bioenergy failures and uncertain returns. Despite agronomic suitability for marginal land and strong carbon capture capacity, high upfront establishment costs and long payback periods create barriers. Participants highlighted the importance of identifying high-value applications beyond energy production, with manufacturing opportunities in insulation and board materials exploiting lignin content as natural adhesive, reducing synthetic binder reliance. Leveraging environmental credentials through carbon accounting or ecosystem service payments could strengthen business cases. UK processing cost benchmarks of approximately £400 per tonne indicate significant investment requirements.

Hemp SWOT: Hemp was reaffirmed as high potential for diversification, particularly on marginal western lands, with yields of four tonnes per acre. However, licensing complexity, THC limits, and insufficient processing capacity (€500,000 per decorticator, €10 million for regional network) impede scaling. Processed fiber (shiv) currently sells for approximately £600 per tonne in UK markets (£2,400 per hectare). Participants proposed cooperative ownership models, long-term licensing reforms, government grant support, and clear certification pathways as essential enablers. Growing demand for hemp-based materials in MMC and retrofit initiatives provides medium-term opportunity contingent upon regulatory streamlining and quality assurance.

Integrated Findings: Across all crops, SWOT analyses revealed common patterns. Strengths lie in Ireland's favourable growing conditions, increasing policy support for circular construction, and availability of agricultural by-products for revalorisation. Weaknesses include fragmented supply chains, lack of processing capacity, high capital entry costs, wet climate, and limited certification and insurance frameworks. Opportunities center on emerging green procurement policies, carbon reduction targets, and potential for regional bio-hubs linking farmers and manufacturers. Threats relate to market uncertainty, competition with conventional materials, and residual perception of biobased products as experimental. Collectively, these analyses underscored the need for coordinated policy instruments—potentially a National Biofibre Plan—to address investment risk, streamline certification, and support early-stage infrastructure development.

V. CRITICAL DISCUSSION

A Irish Supply Chain Pathways: Strategic Priorities and Development Logic

This research identifies distinct strategic pathways for agri-crop biobased construction supply chain development in Ireland, differentiated by resource availability, infrastructure requirements, and market readiness. The findings reveal a clear prioritisation logic based on existing agricultural systems, processing capacity, and investment thresholds.

Straw emerges as the priority pathway for immediate market activation. As a food by-product with established harvesting infrastructure and five existing national chip processors, straw offers the lowest-barrier entry route to biobased construction. The identification of straw chip as blown-in insulative infill (Pathway S1) represents a strategic "quick win"—leveraging existing infrastructure, requiring minimal additional processing investment, and addressing an immediate market need in expanding timber-frame and modular construction sectors. European precedents demonstrate regulatory approval pathways already exist, reducing certification risk. From this foundation, staged expansion toward manufactured products (boards, batts, quilts) provides a development trajectory that de-risks investment through incremental market validation. The estimated Irish straw resource of ~250,000 hectares provides sufficient scale for regional supply chain development without competing with livestock bedding or soil incorporation uses.

Miscanthus represents a complementary medium-term pathway, offering environmental advantages (carbon sequestration, marginal land suitability, perennial growth reducing annual operational costs) but constrained by failed prior bioenergy initiatives and current cultivation limitations. The technical processing pathways (M1, M2) mirror straw, suggesting shared infrastructure investment could serve both crops. However, activation requires overcoming farmer reluctance through guaranteed long-term procurement commitments or ecosystem service payment mechanisms that value carbon and soil benefits beyond fiber production alone. The staggered harvest season (spring for miscanthus versus autumn for straw) presents operational efficiency gains for processing facilities.

Hemp occupies a niche high-value pathway fundamentally constrained by absent decortication infrastructure. The significant investment requirement for regional processing capacity represents a critical bottleneck that cannot be resolved through incremental development. Despite strong farmer interest in contract growing and latent market demand driven by European hemp-lime construction precedents, pathway activation requires either substantial public investment in shared processing infrastructure or cooperative ownership models that distribute capital risk. The dual-use potential of hemp fibre (construction and higher-value textile/composite applications) suggests processing investment should be evaluated within broader industrial crop strategy rather than construction sector alone.

Cross-cutting enablers identified through stakeholder engagement transcend individual crop pathways. Processing infrastructure investment emerges as the universal constraint, suggesting regional biohub models could achieve economies of scope by serving multiple crops. Material certification and testing infrastructure (€70,000 per product, lengthy timelines) represents a market activation barrier requiring coordinated public investment. Demand generation through public procurement policies—particularly social housing, educational facilities, and heritage renovation—provides the market certainty necessary to justify supply-side infrastructure investment. The integration of carbon accounting methodologies and alignment with Corporate Sustainability Reporting Directive (CSRD) requirements positions agri-crop materials within emerging regulatory and financial frameworks.

B Comparison Against European Experience

The Irish findings demonstrate strong alignment with European supply chain dynamics while revealing context-specific divergences that inform pathway adaptation.

Processing infrastructure as the critical bottleneck replicates patterns observed across European case studies. The Netherlands' Building Balance initiative, Belgium's Ecological Building Materials Cluster, and French regional biofiber networks all emerged through coordinated investment in shared processing capacity, validating the Irish stakeholder emphasis on regional biohub development. The identified investment thresholds (€300,000 for basic processing, €2-7 million for manufacturing facilities) align with European benchmarks, confirming capital intensity as a universal barrier requiring policy intervention.

The hierarchical framework developed from European analysis demonstrates direct applicability to Irish pathway specification. The four-dimensional structure (processing technology levels, manufacturing complexity, construction applications, crop characteristics) enabled systematic mapping of Irish pathways) and facilitated stakeholder communication through synthesis mapping. This validates the framework's transferability across different agricultural and construction contexts.

However, Ireland's pastoral agricultural base creates divergence from continental European contexts. The limited tillage area (<300,000 hectares versus millions in France, Germany) and dominance of grassland systems (4.5 million hectares) constrains crop-based supply chain scale. This positions Ireland closer to smaller European economies (Austria, Denmark, Netherlands) where niche regional supply chains serve localised construction markets rather than export-oriented industrial production. The Building Balance cooperative model, designed for Dutch regional markets, may provide a more relevant template than large-scale French or German industrial approaches.

Straw's prioritisation in Ireland contrasts with hemp's prominence in French and Belgian markets, reflecting infrastructure path dependencies. European hemp supply chains benefited from established textile processing infrastructure subsequently adapted for construction applications. Ireland's absence of such infrastructure necessitates a different entry strategy, validating the research finding that pathway selection must align with existing agricultural and industrial systems rather than directly replicating European precedents.

C Contribution to Literature

This research extends the biobased construction supply chain literature through empirical, methodological, and contextual contributions.

Empirically, the identification and specification of crop-specific strategic pathways (Straw S1-S3, Miscanthus M1-M2, Hemp H1-H2) advances understanding of supply chain activation in agricultural contexts lacking established biobased construction infrastructure. While existing literature emphasises technical material properties or environmental benefits (Asdrubali et al., 2015; Pittau et al., 2019), this research demonstrates that pathway viability depends fundamentally on alignment with existing agricultural systems, processing infrastructure, and investment thresholds. The quantification of Irish-specific barriers (processing infrastructure, decortication costs, certification costs) provides actionable intelligence for policy intervention design.

Methodologically, the hierarchical framework synthesising processing levels, manufacturing complexity, construction applications, and crop characteristics provides a structured analytical tool applicable beyond the Irish context. The framework's successful application to both European case analysis and Irish pathway development demonstrates transferability. The synthesis mapping tool represents a practical stakeholder engagement innovation, translating complex supply chain dynamics into accessible visual formats that enabled productive participatory pathway identification.

Contextually, the research addresses a significant literature gap regarding biobased construction supply chain development in smaller, pastoral-dominated economies. Existing supply chain studies predominantly examine large continental European markets (France, Germany, Netherlands) or specialised sectors (Italian hemp, Belgian flax). The Irish case reveals how agricultural structure fundamentally shapes viable pathways: food by-product valorisation (straw) offers lower barriers than industrial crop establishment (hemp, miscanthus) in pastoral systems. This finding has implications for other grassland or straw-dominated economies / regions seeking circular bioeconomy development.

The research also validates and extends recent emphasis on cooperative models and regional bioeconomy hubs (Carus and Dammer, 2018; Lokko et al., 2018) by demonstrating stakeholder convergence on these organizational forms as essential enablers in contexts lacking incumbent industrial infrastructure.

The research has already influenced the Irish Circular Construction Roadmap, with policy recommendations on developing the bioconstruction sector and its supply chains,

D Limitations and Future Research Directions

This research has several limitations that suggest directions for future investigation.

Methodologically, the literature review is non exhaustive and as such - selective representative. The participatory workshop approach engaged a purposive sample of 20+ stakeholder organizations, providing breadth across sectors but potentially limited depth within specific value chain stages. While the multi-stakeholder perspective enabled identification of cross-cutting barriers, future research employing detailed case studies of individual enterprises (farmers, processors, manufacturers, contractors) would provide granular operational insights. The workshop format may have privileged articulate organizational representatives. Future research could focus on direct engagement with farmers through on-farm interviews or grower cooperatives potentially reveal additional farm or economic constraints not fully captured in institutional stakeholder discussions.

Data limitations constrain quantitative pathway evaluation. While stakeholder consultation provided investment cost estimates these represent indicative ranges rather than detailed techno-economic assessments. Future research should develop comprehensive financial models incorporating capital costs, operational expenses, yield variability, processing efficiencies, product pricing, and market demand scenarios to enable rigorous pathway comparison. The absence of established Irish supply chains precluded empirical validation of processing costs, material quality outcomes, or market acceptance; pilot projects implementing priority pathways (particularly Straw S1) would generate essential operational data.

Contextual limitations relate to the study's 2023-2024 timeframe. Policy frameworks and legislation are continue evolving. Regulatory changes affecting agricultural subsidies, construction standards, or circular economy incentives could significantly alter pathway viability. Longitudinal research tracking policy implementation and market development over 5-10 years would capture dynamic interactions between regulatory frameworks and supply chain emergence.

Future research priorities include: i) pilot-scale implementation of Straw Pathway S1 with comprehensive monitoring of technical performance, cost structures, and market acceptance; ii) detailed techno-economic modelling of processing infrastructure investment scenarios, including sensitivity analysis of key variables; iii) comparative analysis with other pastoral economies / regions or nations to identify transferable insights; iv) investigation of carbon accounting methodologies and ecosystem service valuation frameworks to strengthen business cases for perennial crops (miscanthus); v) policy analysis examining optimal intervention mechanisms (grants, procurement mandates, certification streamlining, cooperative support) for supply chain activation; and vi) examination of grass as a biomass resources for construction, given its prevalence in pastoral agri-systems.

VI. CONCLUSIONS

A Key Findings

This research establishes a strategic framework for agri-crop biobased construction supply chain development in Ireland, grounded in literature / European case study analysis and validated through multi-stakeholder consultation. Three distinct pathways emerge, differentiated by infrastructure requirements and market readiness: straw as the immediate priority, leveraging existing agricultural and processing infrastructure for low-technology applications (blown-in insulation, staged expansion to manufactured products); miscanthus as a complementary medium-term pathway offering environmental benefits but constrained by cultivation barriers and prior bioenergy market failures; and hemp as a niche high-value pathway fundamentally limited by absent decortication infrastructure requiring significant investment.

The novel hierarchical framework developed through European analysis—integrating processing technology levels, manufacturing complexity, construction applications, and crop characteristics—demonstrates transferability across contexts, enabling systematic pathway specification and stakeholder communication. Cross-cutting enablers transcend individual crops: processing infrastructure investment, material certification, and demand activation through public procurement emerge as universal prerequisites for supply chain activation.

B Policy and Practice Implications

The findings have direct implications for Irish policy and industry development. A coordinated National Biofibre Plan is recommended to align agricultural policy, construction sector development, and circular economy objectives. This plan should prioritise three intervention mechanisms:

First, strategic public investment in shared processing infrastructure, particularly regional biohub facilities serving multiple crops (straw, miscanthus, potentially hemp). The cooperative ownership models successfully demonstrated in the Netherlands' Building Balance initiative and Belgian regional networks provide proven templates. Initial investment focus should support straw chip and fiberisation processing capacity given immediate market potential in timber-frame and modular construction sectors.

Second, demand activation through public procurement mandates targeting social housing, educational facilities, and public building renovation. Specification of agri-crop insulation materials in public projects creates the market certainty necessary to justify supply-side infrastructure investment. Integration with existing climate action targets and circular economy commitments provides policy coherence.

Third, streamlined certification and testing frameworks to reduce the current €70,000 per-product cost and lengthy approval timelines. Establishment of a national biomaterials testing facility, potentially within existing research infrastructure, would serve multiple supply chains while building domestic technical capacity.

Supporting mechanisms should include farmer contract-growing schemes with guaranteed minimum prices, carbon accounting methodologies that value ecosystem services (particularly for perennial crops like miscanthus), and cooperative development grants to facilitate collective ownership of processing infrastructure.

C Future Directions

Pilot-scale implementation of Straw Pathway S1 (chip insulation in timber-frame construction) represents the critical next step, generating operational data on processing costs, material performance, and market acceptance. This should be coupled with analysis of grass for potential biobased applications, along with comprehensive techno-economic modelling across all pathways to inform investment prioritisation. Comparative research with other pastoral economies (New Zealand, Scotland, Wales) would identify transferable insights for smaller-scale bioeconomy development. Longitudinal tracking of policy implementation and supply chain emergence over 5-10 years will capture dynamic interactions between regulatory frameworks, market development, and agricultural adaptation. Integration with broader bioeconomy strategy—encompassing textiles, bioplastics, and biochemicals—positions agri-crop processing infrastructure within diversified value networks, strengthening business cases through economies of sale.

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Credit - authorship contribution statement.

Patrick Daly: Principle investigator / researcher / author / supervisor, undertaking - conceptualisation, methodology, investigation, data, analysis, visualisation, paper writing, review and editing.

Declaration of Competing Interest.

No potential conflicts of interests are reported by the author.

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Razvoj strateških poti v oskrbovalni verigi za uporabo kmetijskih pridelkov kot bioloških gradbenih materialov, izdelkov in modularnih sistemov

Izvleček – Gradbeni sektor prispeva 37 % svetovnih emisij ogljika in 40 % odpadkov v EU, kar spodbuja politične pobude za dekarbonizacijo in krožno gospodarstvo. Čeprav biološki materiali ponujajo nizkoogljične alternative, njihova omejena uporaba odraža sistemske ovire v oskrbovalni verigi in ne tehnično neustreznost. Ta raziskava razvija in uporablja nov hierarhični okvir za kartiranje oskrbovalne verige, da bi identificirala strateške poti za gradnjo iz bioloških kmetijskih pridelkov na Irskem, s poudarkom na slami, konoplji in kitajski trstikovec oz. miskantus. Razvit je nov štiristopenjski okvir za kartiranje oskrbovalne verige, ki vključuje kompleksnost predelave in tehnološke ravni, uporabljen pa je bil v dveh nacionalnih delavnicah za zainteresirane strani, v katerih je sodelovalo več organizacij iz kmetijskega, proizvodnega, gradbenega in političnega sektorja. Analiza razkriva vrsto potencialnih oskrbovalnih verig, ki segajo od nizkotehnoloških aplikacij (bale, izolacija z vpihovanjem) do industrializiranih izdelkov (plošče, bloki, modularni paneli), pri čemer sta predelovalna infrastruktura in certificiranje opredeljena kot ključna ozka grla. Irski delavnici potrjujeta slamo kot prednostno pot, pri čemer izkoriščata obstoječo infrastrukturo za žetev in sekanje za takojšen vstop na trg prek lesene konstrukcije in modularnih sistemov, s postopno širitvijo v smeri napredne predelave vlaken. Konoplja predstavlja visokokakovosten nišni potencial, odvisen od zmogljivosti luščenja, medtem ko kitajski trstikovec ponuja dolgoročne dopolnilne koristi. Medsektorski dejavniki vključujejo regionalna predelovalna središča, pospešeno certificiranje, javna naročila in usklajene okvire politik. Novi hierarhični okvir kartiranja in poti, ki so jih potrdile zainteresirane strani, zagotavljajo strukturiran načrt za pretvorbo kmetijskih stranskih proizvodov v uporabne gradbene vire, ki se lahko uporabijo v podobnih regionalnih in nacionalnih kontekstih.

Ključne besede – gradnja na biološki osnovi, kmetijske kulture, kartiranje oskrbovalne verige, strateške poti