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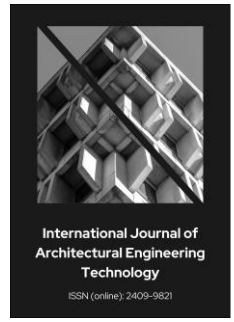

Biobased Construction from Agricultural Crops: Paper 2 - Supply Chain Dynamics of European Case Studies

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ABSTRACT

Energy security, economics and environmental factors are key drivers toward greater energy efficiency, decarbonisation and circularisation of the building sector.

Bio-based construction provides a potential low carbon and circular strategy toward these aims, as these materials can sequester carbon, are derived from renewable and nontoxic sources and can be re circulated in either technical or bio cycles.

This innovative research undertakes a state of play into select agri-crop biobased construction materials, products and systems across Europe focusing on their supply chain types and dynamics.

The research is based on a multi case study applying a range of mainly qualitative research methods, including desk-based review, semi structured interviews and supplemental field work facilitating a high-level analysis of this sector and its supply chain dynamics.

This novel research presents an overview of the sector and examination of supply chain dynamics in relation to key agricultural, process, manufacture and construction stages.

The findings show an emerging biobased construction sector utilising a range of agri-crops to produce various materials, products and modular systems within diverse and innovative supply chains, with common and distinct features and aspects identified including; crop types and utilisation, processing requirements and methods, transport, handling and storage, construction application, the centrality of certification and testing to access markets and growing interest in carbon profiling and benefits.

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1. Introduction

The building and construction sector has a significant environmental impact, consuming approximately 34% of global energy demand and generating 37% of energy and process-related carbon dioxide emissions [1], with the sector also producing a considerable amount of construction and demolition waste (CDW), for example accounting for around 40% of all waste generated in the European Union [2].

Given these environmental impacts and the sector's economic importance, Europe has implemented substantial policy and legislative measures to improve the sustainability [3] and energy efficiency [4] of its building stock. Policy initiatives have increasingly focused on transitioning the economy and the building sector towards more circular practices [5] driven by the construction sector’s high resource intensity and waste production [6, 7].

Notable among Europe's policy and legal initiatives are the Renovation Wave [8] and the EU Green Deal [9], which aim to decarbonize the existing building stock, improve energy efficiency, promote renewable energy, and reduce and recover construction waste. Additionally, the Circular Economy Action Plan encourages circularity principles for the construction sector [10].

In Ireland decarbonisation and circularity are also being promoted through the Irish Climate Action Plan [11], the introduction of a Circular Economy Act [12], with the Irish Green Building Council developing frameworks and roadmaps to support decarbonisation and circularity of the building sector in particular [13, 14].

Biobased materials are an important pathway to decarbonising and circularisation of the construction sector and generally refer to materials that derive from living matter – biomass, occurring naturally or synthesised from same [15]. Within the construction sector the principle resources for biobased materials derive mainly from agriculture and wood industry and are used in a diversity of applications including load-bearing and non-load-bearing construction, cladding, insulating, sheeting and plastering materials. While timber is one of the most common biobased materials used in construction, there is a diverse range of other resources being utilised, such as straw, hemp, cork, shells, husks, reeds etc. In addition to a range of potential environmental, (low toxicity, renewable non virgin sources, biodegradable etc.) and carbon benefits of these materials, there are also claims of positive thermal and moisture properties, notably combined insulation and thermal inertia with improved hygroscopicity and moisture buffering [16].

Agricultural crop biobased materials are argued to be low environmental impact across all life cycle stages, being simple to produce, moisture resistant, potentially long-lasting, locally accessible, have good thermo-physical properties, are low toxicity, low embodied energy, with high potential for circularity, and minimal ultimate waste [17].

Importantly the resource availability is substantial with supply of forestry, agriculture and biomass residues outweighing projected construction demand, and that other applications and end of life pathways, such as energy recovery, miss out on the carbon capture aspect of these long-life building materials. Notably, compared with wood-based bio constructions, crop-based bio constructions can result in even lower carbon emissions [18, 19].

While biobased materials provide a potential pathway to sustainable low carbon construction, the sector is presented with many challenges including, the sheer diversity of resources and variations, technology development, economic viability and competitiveness, and compliance with regulatory performance standards, which are often tailored for different material typologies [20].

While the potential adoption of crop-based biomaterials remains relatively untapped [17], this research, on the emerging commercial applications of argi-crop materials in construction, shows evidence of a diversity of biobased construction solutions being commercially applied in mainstream construction across a diversity of supply chains.

Carried out by Irish research partners of the Circ Reno project, an EU inter-regional initiative promoting biobased construction supply chains from agricultural crops and demonstrating their application in social housing retrofits [21], this research aimed to synthesise knowledge on contemporary European commercial applications of straw, miscanthus, and hemp construction materials, products, and modular systems to support similar solutions and supply chain developments in Ireland.

2. Research Approach and Methods

This innovative research was conducted to gain insights and knowledge on the commercial development of key agricultural crops—straw, miscanthus, and hemp—into biobased construction materials and solutions in Europe and in particular to examine and determine types of supply chains and their key dynamics and aspects.

The research, based on a multi case study, explored the extent and scope of commercial applications of straw, miscanthus, and hemp crops in biobased construction across Europe. It investigated which materials, products, and systems are being produced / manufactured and how they are being applied in construction, with a focus on their supply chain aspects and dynamics.

The research utilised several approaches and methods, primarily qualitative in nature and drawing from case study research [22, 23], to gather and analyse the data, as follows.

A scoping literature review was conducted to establish the context, key drivers, and an overview of biobased construction and supply chain mapping.

A detailed, though non-exhaustive, desk-based review was performed on known suppliers, producers, and manufacturers with supplemental communications. Data was collected and tabulated regarding material/product properties, applications, testing, certification and claimed benefits.

A series of semi-structured interviews (supplemented by several field studies and site visits), were carried out with a representative sample of 13 companies from across the supply chains, including growers, processors, and manufacturers, which facilitated case study analysis and high-level supply chain mapping. Fig. (**1**) represents a schematic overview of the research.

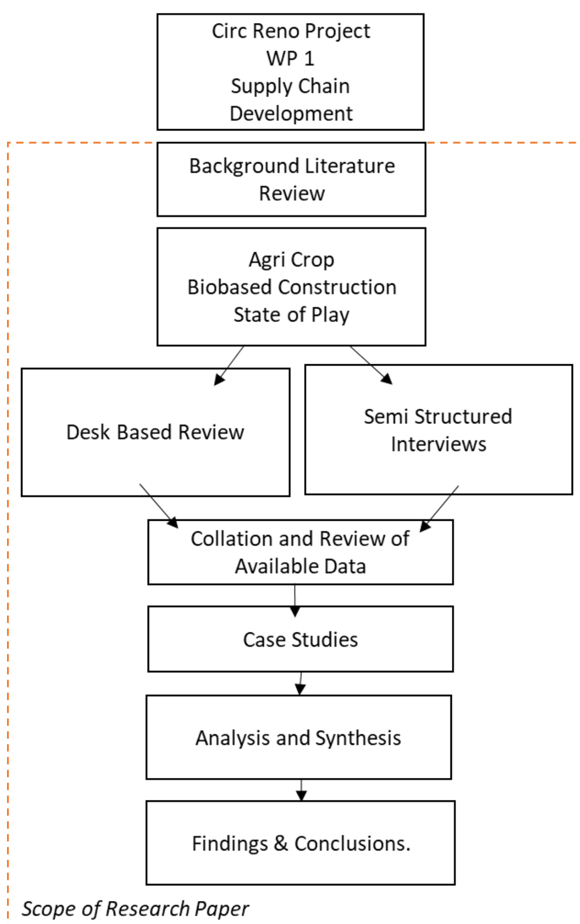

Figure 1: Schematic of the research scope and stages in undertaking the state of play of commercial application and supply chain dynamics of agri-crops in biobased construction [Source Authors].

The study represents research that is in progress and a ‘snapshot’ in time, and as such the representative companies are not exhaustive and the number of companies and associated solutions examined may expand over the course of the Circ Reno project and beyond.

The study has focused on dedicated commercial companies actively producing materials, products or systems for application in construction and ignores the alternative farm direct supply of materials, such as supply of straw bale, which has significant application in Europe.

The research paper contributes to several UN Sustainable Development Goals including 7, 8, 9, 11, 12, 13 and 15.

3. Agricultural Crops in Biobased Construction

This section presents an overview of key agricultural crops, straw, miscanthus and hemp, and their application and commercial activity in biobased construction in the European context.

3.1. Agri Crop Resources

i) Straw

Straw is the leftover stalk from harvested grains / cereals [24] consisting mainly of cellulose, hemicellulose, and lignin [25], and is mainly used for livestock bedding or as biomass energy crop [26], or incorporating into soil to increase soil organic carbon levels [27], but also has construction application as bales, chips or to fabricate boards and batts.

Straw is abundantly available across Europe, at approximately 50.69 million hectares [28], producing some 270 million tonnes of cereal [29], with an established harvest and processing sector.

ii) Hemp

Hemp (cannabis sativa L.) is a rapidly growing, multi yield industrial crop consisting mainly of cellulose, hemicellulose and lignin [30], that has a range of applications in a diversity of sectors [31], with processing separating the fibre from the woody inner part of the stem to shives [32], with both the fibre and shiv having potential application in construction [33].

The hemp resource in Europe is relatively minor but sufficient to supply hemp on industry scale, with hemp cultivation at 28,030ha in 2023, producing circa 158,150 tonnes [34] with France being the leading producer [35].

iii) Miscanthus

Miscanthus is a large perennial grass [36], that remains productive for 20-25 years, thrives on marginal lands, can help remediate soils, and is non-invasive [37]. Consisting of mainly cellulose, hemicellulose and lignin [38], miscanthus has a wide range of core applications across various sectors, with potential construction uses [37].

Miscanthus is also a relatively minor crop in Europe, with an estimated 20,000 hectares of land under cultivation in the EU in 2016, however, its cultivation has been decreasing in many regions [39].

3.2. Biobased Solutions Commercial Activity

i) Overview

Some, 57 companies were identified and reviewed in this research, with 46 engaged in the supply and manufacture of agri-crop biobased materials and products, and 15 incorporating these resources into modular construction systems. See Appendix 01 for list of companies reviewed.

Companies involved in supplying straw-based construction materials and products are widespread, encompassing manufacturers of straw bales, blow-in straw, boards, batts, and various straw based modular systems. While straw remains the predominant resource, there is a higher numerical presence of companies manufacturing hemp-based biobased materials and products. A significant cluster of these companies is in Western Europe, particularly in France, Germany, and the Benelux countries, likely benefiting from proximity to significant regional resources. However, it was noted that several companies also utilise imported hemp resources (Fig. **2**).

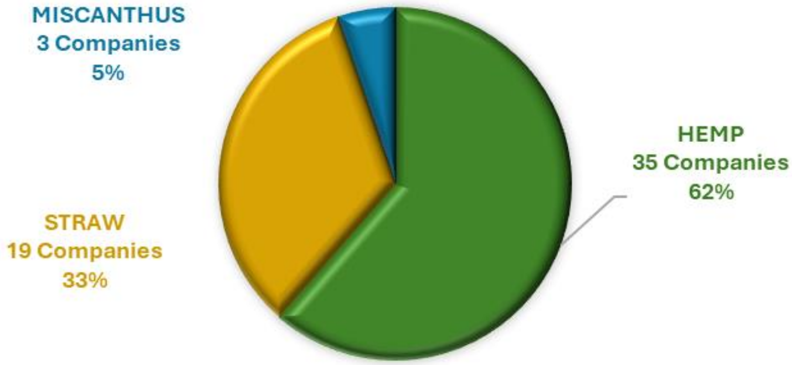

Figure 2: Companies sourced involved in the manufacture of biobased materials, product and/or modular systems by resource type, straw, hemp, miscanthus (ignoring farm direct resources) [Source Authors].

ii) Materials and Products

Approximately 46 of these commercial companies were identified as involved in manufacturing biobased construction materials and products derived from agricultural crops such as straw, miscanthus, and hemp, with hemp companies being the most numerous. Notably, hemp companies are primarily concentrated in Western regions, while straw-focused enterprises are more prevalent in Eastern regions, ignoring dispersed farm direct bale production. The locations and proportion of companies active in supply of materials and manufacturing products, by resource type could be seen in Fig. (**3**).

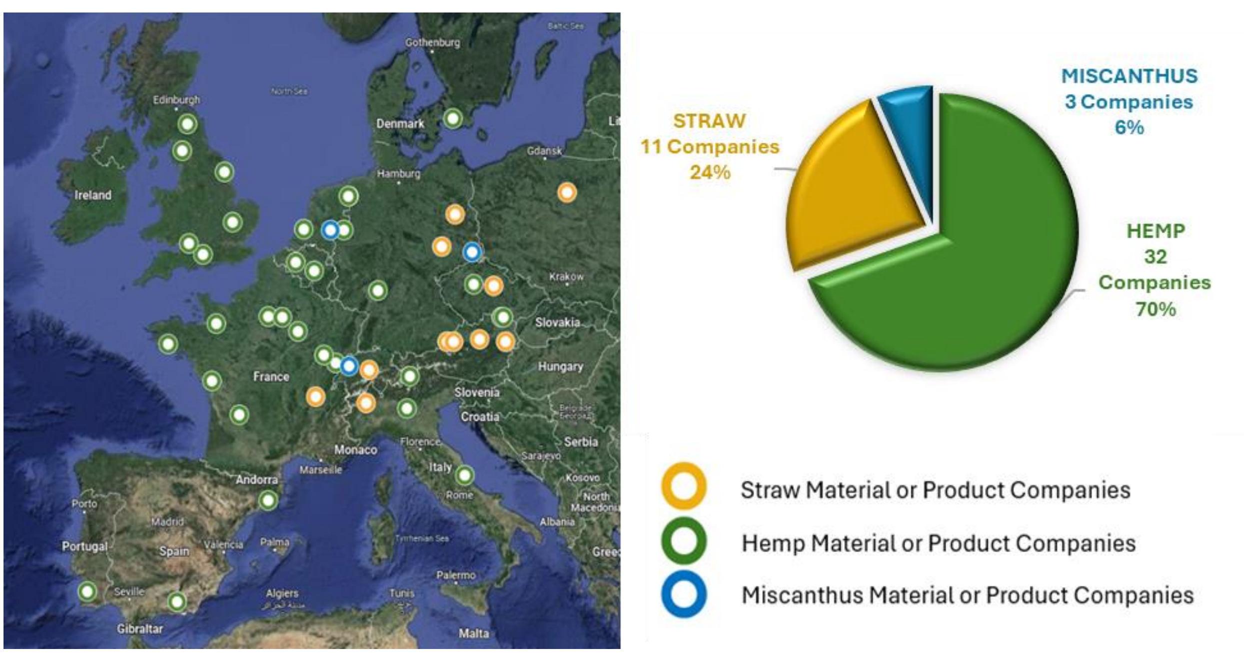

Figure 3: Companies active in supply of biobased materials and products across Europe, LHS - location map, RHS proportion of companies, all by resource type [Source Authors].

Of the companies reviewed, most of the biobased solutions were non load bearing materials and products across a of range of technology / complexity levels, mainly applied in timber framed construction, based on both wet and dry systems and including low technology solutions such as straw bale, low – medium technology level solutions like wet hempcrete infill and blow in straw, and a range of medium technology level boards, batts and quilts, and examples of block manufacturers mainly non load bearing. There were also innovative companies extracting sub materials from these resources for application in other material and products, e.g. cellulose, lignin, fibres, etc.

Straw is being utilised in a range of ways and technology levels including bales, blow in insulation, and boards / batts of varying density and thermal performance, all applied in timber frame constructions. Hemp based companies, were the most dominant of the material and product companies and are producing hempcrete for timber fame infill and masonry block application but also a significant range of medium tech products such as boards, batts and quilts for application in timber construction. One example of miscanthus board was found. See Fig. (**4**) for an overview of the range and types of agri-crop biobased materials and products by broad technology – complexity level.

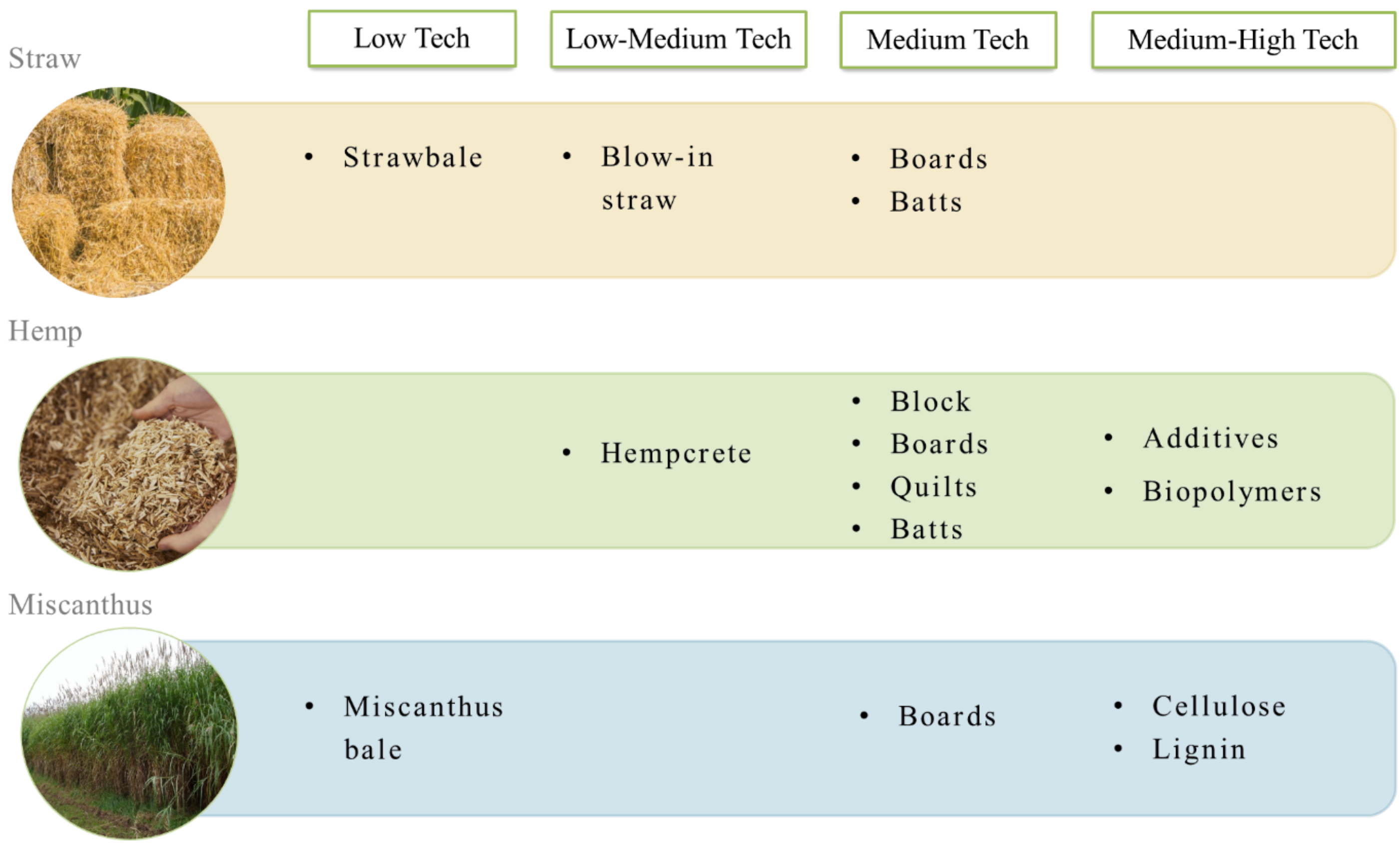

Figure 4: A summary chart of the type of application of agri-crop biobased materials and products under broad technology – complexity levels [Source Authors].

iii) Modular Systems

Fifteen companies were observed to specialise in manufacturing modular systems using these agricultural crops. While some modular companies operate primarily within their regions, many export across Europe, and several are planning to expand their manufacturing capacity and establish new plants (Fig. **5**).

Straw was found to be the more dominant of the modular systems reviewed, followed by hemp and one example of miscanthus. Straw panels are mainly dry system based wall and roof panels, employing various technology levels such as compressed bales or use of loose chopped straw – applied in a range of methods including blow in, mainly utilising twin stud / structural systems with a diversity of panel sizes in both open and

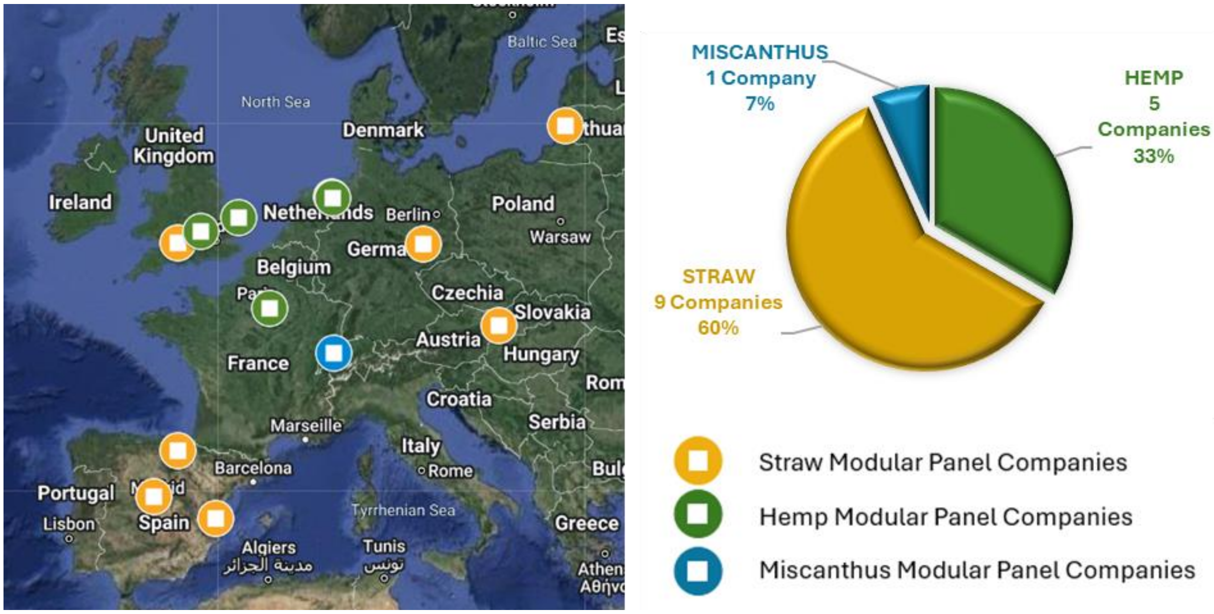

Figure 5: Companies active in supply of biobased modular systems across Europe - LHS location map , RHS % pie chart, all by resource type, straw, miscanthus, hemp [Source Authors].

closed solutions, being applied mainly in new building but with some retrofit examples. In contrast, hemp modular panels utilise mainly wet systems with varying dry times depending on the components and build ups. They primarily employ single stud frames, tending to be larger panels with both open and closed system examples, and targeting mainly new buildings. The sole miscanthus system was very similar in typology to hemp solutions. See Fig. (**6**) for an overview of types and key characteristics of modular systems by resource type.

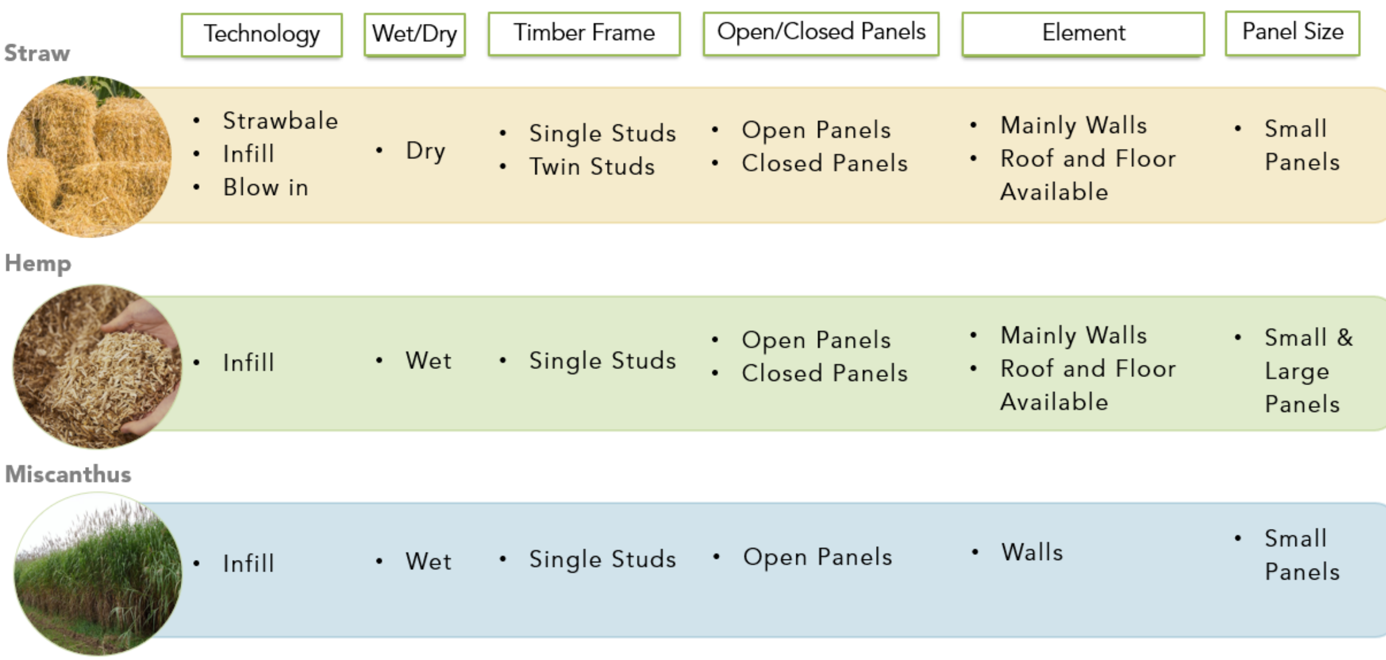

Figure 6: A summary chart of the main characteristics of the modular panel system per resource type [Source Authors].

For further detail on these key agri-crop biobased materials, products and modular systems their types, characteristics, key performances, testing certification etc., please refer to the precursor paper *'Biobased Construction from Agricultural Crops Paper 1 - A State of Play of Commercial Solutions in Europe'* [40].

4. Supply Chain Case Studies

This section presents an overview of the supply chains of a representative sample of companies derived from semi structured interviews with a focus on more detailed case studies / supply chain mapping of six companies representing different; locations, resource use, supply chain stages, processing and material, product and system outputs and construction applications.

4.1. Supply Chains / Mapping

Supply chains have been broadly defined as a process or flow of goods (and services) wherein they are transformed and supplied to others for a particular function or utility, typically for financial benefit [41, 42]. Supply chain models and dynamics have some co-relation to general systems theory [43], and are seen as a particular form of system, with specific inputs, processes and outputs and distinct boundaries [44]. Mapping or schematic representation of the system / supply chain is seen as an important tool in the design, understanding and management of supply chains, with approaches subject to purpose, with differences in level of hierarchy, detail and functionality [45, 46].

In this research high level supply chain mapping, in line with a meso level perspective from MacCarthy *et al*. [46], is utilised to assist in system analysis to help define, characterise and compare a range of agri-crop bio-based construction supply chains – identifying key supply chain actors, resources, activities, outputs and issues across four key stages, 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. Fig. (**7**) presents a schematic model and scope of the meso level supply chain mapping undertaken.

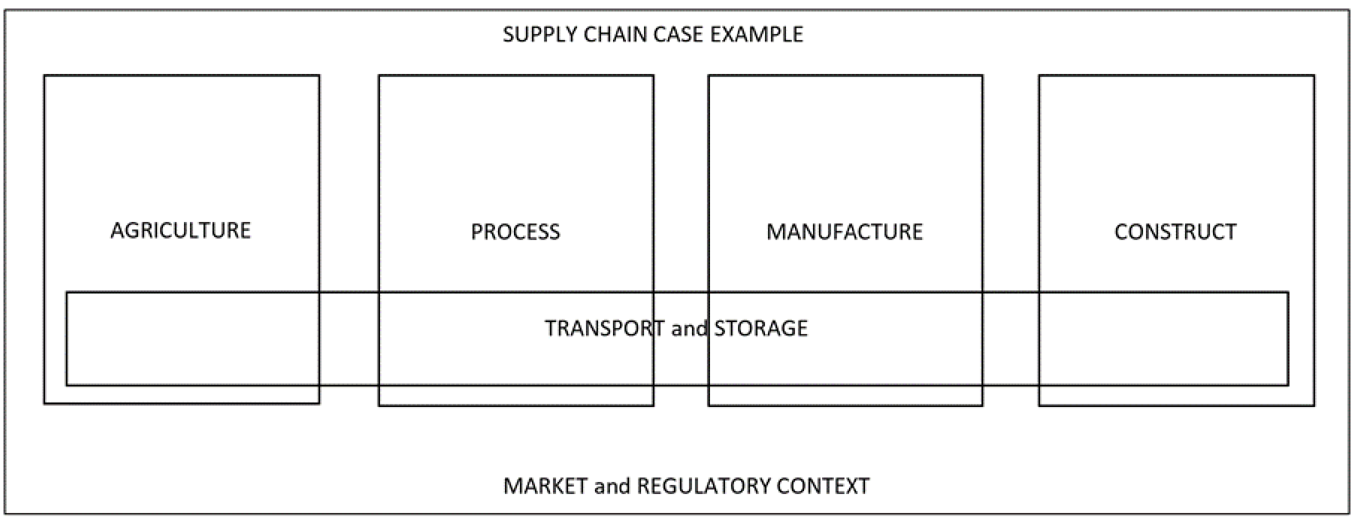

Figure 7: Showing schematic of scope and categories of high level supply chain mapping exercise conducted in this research across four key supply chain stages, agriculture, process, manufacture and construction [Source Authors].

The data sources for these maps were accrued from circa 13 semi structured interview (supplemented with some site visits), from a representative sample of over 50 reviewed companies across Europe active in processing and manufacture of bio-based materials, products and systems from straw, hemp and miscanthus.

4.2. Supply Chains – Sample Companies Overview

Table **1** presents an overview of the representative sample companies who engaged in semi structured interviews showing four identified key supply chain stages, agriculture, processing, manufacture and construction application, noting companies focus, resource crop and supply chain stage noted with commentary.

Table 1: Presenting a supply chain overview of representative sample of companies [Source Authors].

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.

*Showing representative companies for more detailed case study.

This overview highlights the diversity of the sector with a range of resources being utilised, their various processing methods and modes (third party or in house), range of material and products being manufactured, including their integration into modularised systems, and type of construction applications noting bias toward timber framed structures for most insulative infills, boards, batts and quilts but also some non-load bearing masonry applications and that multi story and non domestic buildings are also utilising these solutions and systems.

4.3. Selective Case Studies / High level Mapping

A range of more detailed specific case studies / high-level mapping exercises was undertaking, representing processing, manufacture and construction stages, to analyse supply chains in more detail - highlighting key similarities and distinctives as follows;

i) Specialist Miscanthus Processor (Germany)

Description / Context

This case is a specialist miscanthus processor in Germany supplying into several sectors / industries in Germany and Europe including the construction sector.

Resource

The processor utilises circa 170 ha of miscanthus under contract growing and open market including its own 20 ha farm, which it mainly uses for specialist varieties and trials.

Processing

The processor is highly specialised and utilises specific varieties and processing techniques, primary and secondary, to supply into to a range of sectors such as pharmacy, paper, plastics, car panels, animal bedding, biomass and construction sectors. Some of the key element's output from the plant are cellulose, fibre, silicone, pith, and shiv chips of varies sizes.

Construction Application

In addition to other sectors, they supply a diversity of materials to companies producing a range of construction products such as, blow in chips for insulation, thatch for roofing, 'miscrete' (miscanthus – lime) blocks, mycelium acoustic boards, construction boards and panels. See Fig. (**8**) for high level supply chain mapping.

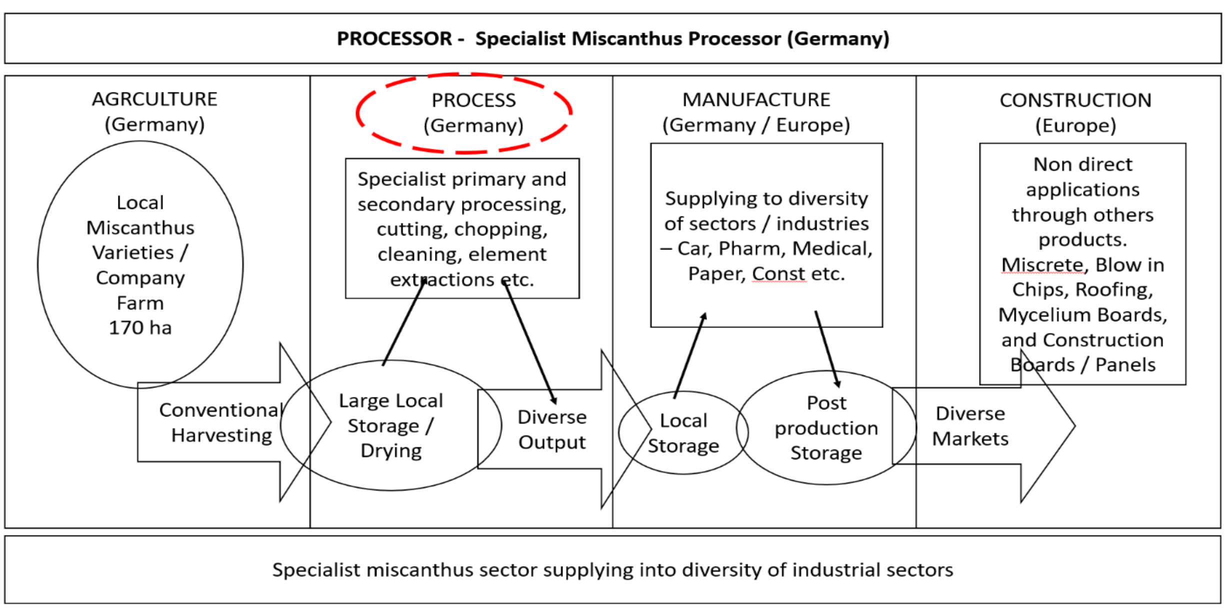

Figure 8: Presenting a high-level supply chain mapping of specialist miscanthus processor tailoring its processing to supply a range of sectors / industries with raw materials for third party manufacture including the construction sector [Source Authors].

This case highlights the following key aspects; an in-depth knowledge of miscanthus agronomy including diverse varieties with owner trials plantation / farm, highly specialised processing / sub processing - tailored to multiple client needs - serving a diversity of sectors / industries.

ii) Straw Processor / Construction Material (Austria)

Description / Context

This case is a straw processor / material supplier in Austria, supplying both construction straw bales and blow in straw chips.

Resource

The company developed out of agricultural straw processing for animal bedding and uses circa 1000 ha of straw (round bale) from a small number of larger growers in their region, initially focused on supply of straw bales for bale construction, and later expanding to chopped straw for insulative infill.

Process / Manufacture

They supply two main products i) straw bales either direct from farm or from their plant where they can re-process straw to particular and consistent sizes and quality to certified standards and ii) a straw chip for blow in insulation infill, which involves cutting / chipping, dedusting and bagging of the product for storage and distribution. They also undertake straw construction consultancy and local sample testing for certification of both bale and blow in chip insulation.

Construction Application

The straw bale product is primarily aimed at new build timber frame housing, mainly walls, and the blow in straw insulation is being used mainly in new build timber framed buildings for walls and roofs and sometimes in floors, with potential retrofit application.

The company supplies regionally across central Europe and has European Technical Assessments (ETA) and associated CE (European Conformity) certifications for both straw bale and blow in infill. See Fig. (**9**) for high level supply chain mapping.

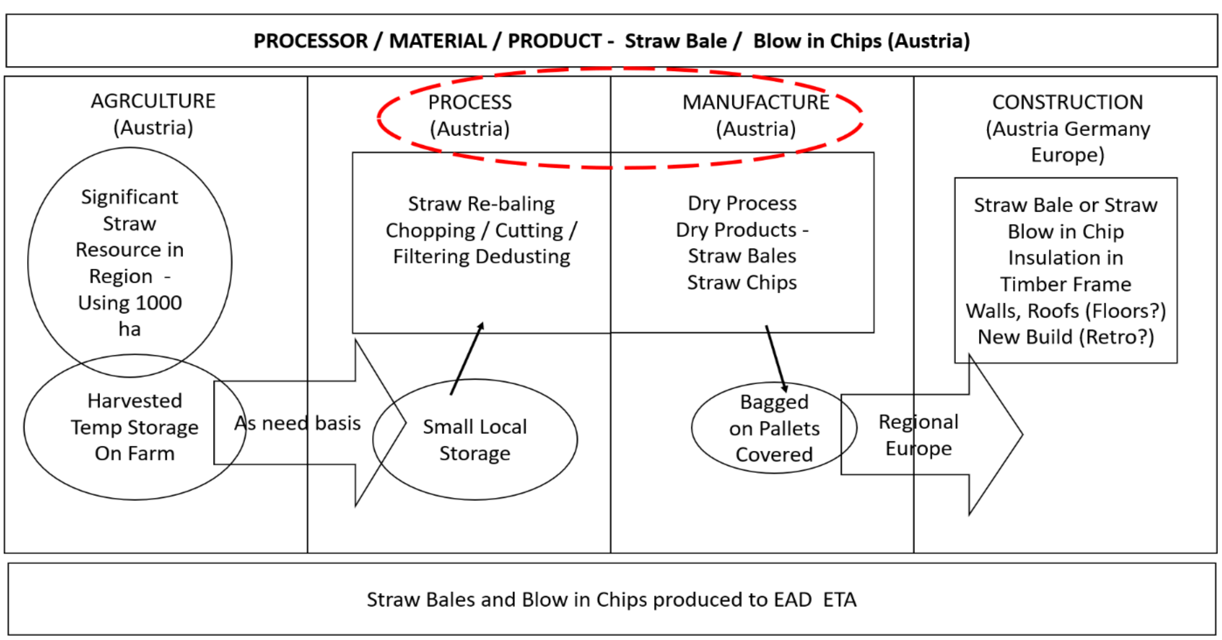

Figure 9: Presenting a high-level supply chain mapping of a straw bale / chip processor supplier for timber frame construction with either straw bales or a blow in straw chip insulation infill [Source Authors].

This case highlights the following key aspects; company and product developed / diversified out of existing knowledge and capacity, expanded from bale construction experience to blow in straw chips, based on large volume straw resource availability, focused on timber frame construction, outsourcing storage to supplier, have secured key ETA certifications for trading across Europe, and provides consultancy and testing support.

iii) Straw Based Construction Products (Poland)

Description Context

This case is an innovative Polish company who have developed patented technology for straw fibre extraction to manufacture a range of straw fibre-based boards, batts and loose fill insulation.

Resource

The small factory has access to a significant straw resource, with direct access to a diversity of cereal farmers / straw suppliers in their region, utilising some 1000 tonnes of straw directly from farmers within a 30 - 50 km region on an annual contract basis. Resources are stored on farm (covered) and generally delivered to factory on an 'as need' basis into a smaller local storage area, thus reducing need for large scale factory storage at harvest. Moisture content is typically 15% though less critical as the production process is wet based.

Process / Manufacture

The company is a combined processor / manufacturer, involving a patented wet process for fibre extractions before manufacture of a range of boards, batts and quilts, via pressing and combining with additives such as polymers and recycled fibres. They also supply the fibre as a low density (45-75kg/m^3) blow in insulation. Products are then packed and stored for transport and delivery through direct sales and supplier network.

Construction Application

The materials and products are mainly applied in timber frame construction, mostly walls and roofs, as inner and outer frame liners, internal insulation fill and an external wall insulation. The products are used in housing and non-domestic buildings, mainly new build but with potential for retrofit application. They are also being applied in historic building conservation projects where vapour open (breathable) construction is required.

They supply mainly across continental Europe noting some limitations due to transport costs and some national and regional certification barriers, despite products having CE marking based on harmonised standards. See Fig. (**10**) for high level supply chain mapping.

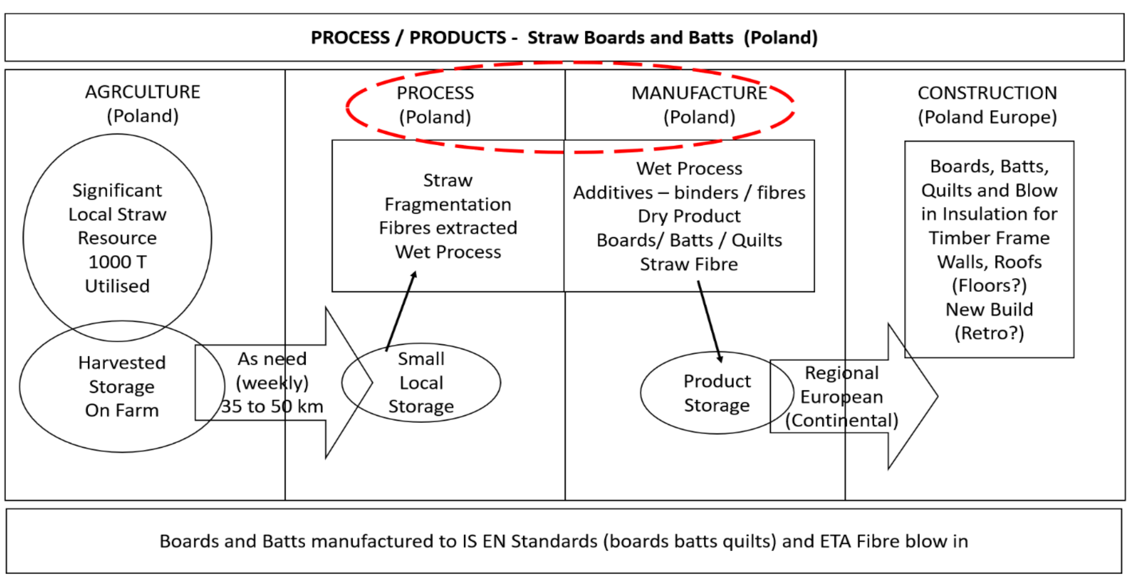

Figure 10: Presenting high level mapping of straw-based processor / product manufacturer with patented technology for fibre extraction of straw, manufacturing and supplying a range of boards and batts for timber frame construction and fibre blow in insulative infill [Source Authors].

This case highlights the following key aspects; building supply chains around large available resource, outsourcing of storage to supplier, manufacturing under patented technology, products that are stackable and transportable, and have appropriate certification, blow in straw fibre with lower density than straw chip blow in.

iv) Hemp Based Construction Material and Products (Italy)

Description / Context

This case example is of a hempcrete supply and hempcrete block manufacturer, which is a subsidiary of and integrated into a larger cement construction product company in northern Italy.

Resource / Processing

Hemp shiv, manufactured to the French hemp construction associations, (Construire en Chanvre) quality standards, is imported by road some 900 km from France to the plant in northern Italy for application in both hempcrete infill and masonry block manufacture, where it is bulk stored in covered sheds. (There is openness to secure a more local or regional hemp resource, subject to equivalence of the French quality standard).

Manufacturing

The hemp shiv is i) supplied in large and small bags for application with their propriety lime / probiotic binder / water in 'hempcrete' mix for infill solutions in timber framed walls, roofs and floors, and ii) for manufacturing of hemp blocks via an adapted processing line within an existing block making plant, involving mixing the hemp with water and the proprietary lime binder, pressing into mechanical moulds before later stacking, drying and wrapping / storing. The company also provides training, installation and consultancy services.

Construction Application

The 'hempcrete' is mainly used as an insulative infill in new build timber frame walls, roofs and floors with some retrofit applications. The masonry blockwork is typically nonloadbearing and used within post and beam structures.

The company is mainly operating across Italy and central Europe but also has some international exports. They have secured key thermal and fire certifications under International and European Standards (IS) (EN) standards as well as Environmental Product Declaration (EPD) environmental testing. Fig. (**11**) presenting high-level mapping of this hemp product supply chain.

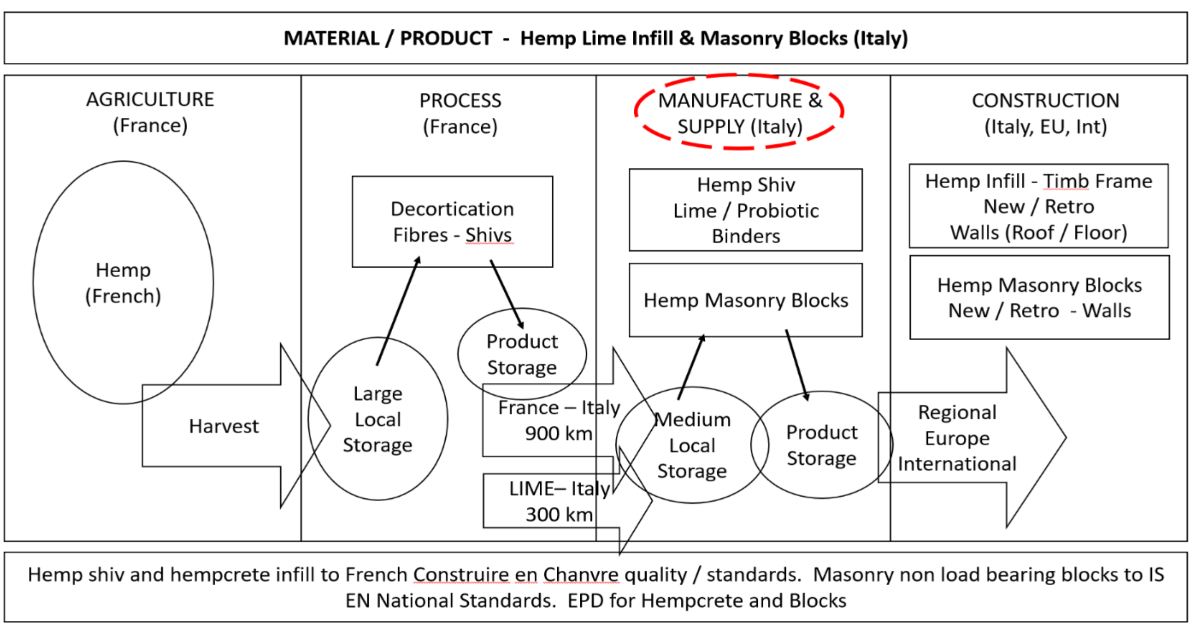

Figure 11: Showing a high-level supply chain mapping of this hemp lime supplier/manufacturer based on French hemp resource [Source Authors].

This case highlights the follow key aspects; that supply chains can function remote from resource, that existing knowledge and production facilities can be adapted to develop biobased products, that training and consultancy are key aspects of service for mainstream integration of the solutions in commercial projects, and use of patented binder based on innovative probiotic technology for enhanced drying times.

v) Hemp Based Modular Wall System

Description Context

This case study is based on a hemp based modular wall system manufacturer located in northern France part of the Construire en Chanvre association who provide quality assurance standards for hempcrete product and construction [47].

Resources

The supply chain is based on a well-developed industrial hemp sector with some 100 farmers growing hemp within a 25 km radius of which the modular manufactures currently utilises some 1000 ha of processed hemp shiv.

Processing

The third-party processor has a large storage facilitate and decortication plant for separation of the fibre from the plant stem (which can be used to make quilt insulation), and the remaining woody core component of the plant - shiv being chopped to a particular size and de-dusted for application in 'hempcrete'.

The modular manufacturer is located next door to the processor, with minimal transport and no large volume or long-term storage needs, being supplied on an 'as need' basis via bulk supply into a storage silo, for later mixing with lime and water to produce the bio-composite hempcrete.

Manufacturing

The factory comprises several assembly and storage / drying areas. The modular walls are based around a single timber stud frame system, which are assembled on a horizontal bed, lined on one face and with temporary shuttering around edges and openings to receive the hempcrete infill from a hopper, which is simply raked into the timber frame. The panels are stored on the assembly beds for 8 to 72 hours, for initial lime set, and then raised vertically for additional work and completions, i.e. installing windows and doors, internal or external claddings etc., and additional 21 days storage for full drying before external transport and delivery to site. The plant has a capacity of approx. 30 panels per week.

Construction Application

The wall panels are generally load bearing, with two types, one for two story and one for multi-story, but are also utilised as semi or non-load bearing within post and beam structures. The panels are being applied in mainly single and double story domestic buildings but also in multi-story apartments and other non-domestic building types.

The supply chain operates mainly regionally in northern France and the company are seeking to establish a second plant in southern France and one overseas. The manufacturer operates under construction material and product certification and testing carried out by the association, Construire en Chanvre, but are also undertaking their own testing for more advanced performances. See Fig. (**12**) for high level supply chain mapping.

This case highlights the following key aspects; operating in context of a well-developed hemp industry and hemp construction sector with national association quality standards and certification, advantages of proximity to resource and processor, challenges of use of wet material with drying stages and storage in assembly line, application in multi-story buildings and plans to establish several regional and overseas plants.

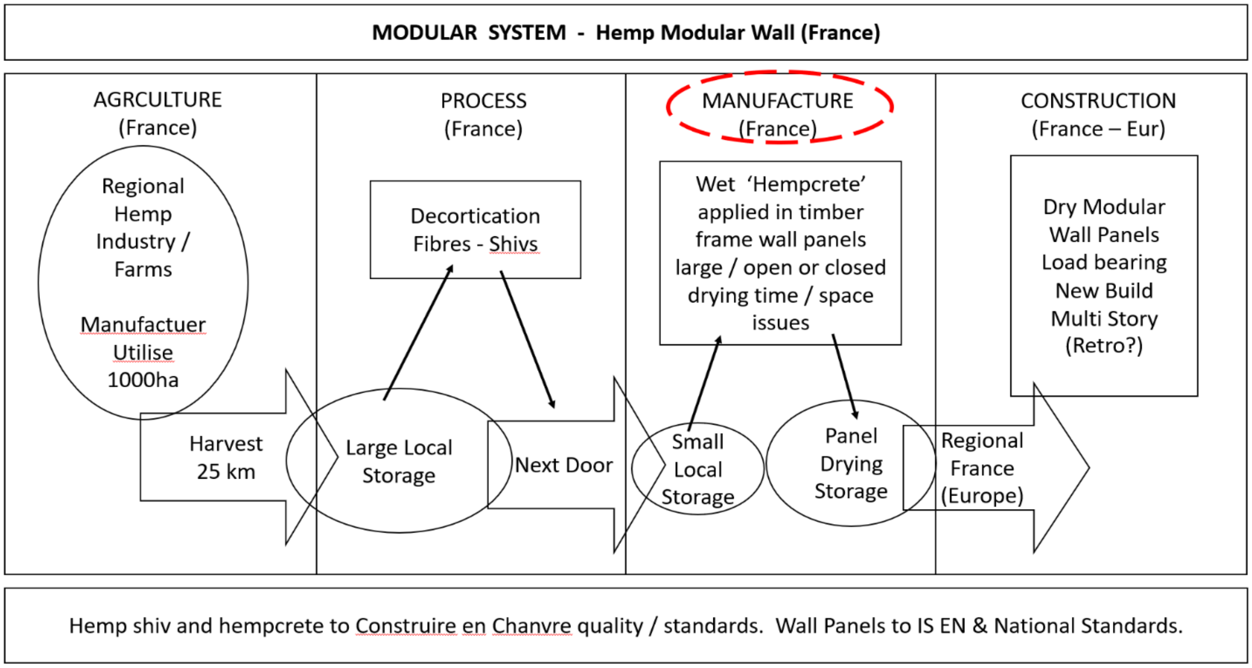

Figure 12: Presenting high-level supply chain mapping of this wet process hempcrete based modular wall panel manufacturer located adjacent to processor and seeking to develop several regional factories [Source Authors].

vi) Straw Based Modular Wall System

Description / Context

This case is an innovative straw based modular system manufacturer based in Lithuania and Slovakia utilising automative production and are seeking to develop other factories in Europe.

Resource

The modular system uses compressed straw as an insulative infill from straw resources which are locally / regionally available across Europe.

Process / Manufacture

The manufacturer is also the main processor and receives large volumes of mainly rye straw, (5000 – 6000 round bales) at winter harvest for long term storage / drying (1–2 years), with the process involving cleaning, chopping, dedusting and compressing the straw into a modular wall panel. The modular wall panels are twin stud, small panel and 'open' i.e. only partially finished, to aid stackable storage, transport and handling. These modules can be sent direct to site for assembly and closing out or be further assembled and closed (completed) in local temporary factories for site installation

Construction Application

The modular panels are wall systems only, generally loadbearing up to 6 storeys, but can also be installed in post and beam structures and are primarily focused on new build applications, but with interest in developing modular retrofit systems.

The company are supplying across Europe and are developing other plants, notably strategically located close to urban centres and transport hubs and ports for ease of shipping rather than proximity to resource.

They have national testing for the products and are seeking European Technical Assessment (ETA) certifications for their straw system. They report some challenges in terms of local, regional and national regulatory standards and test requirement variation, especially for fire. See Fig. (**13**) for high level supply chain mapping.

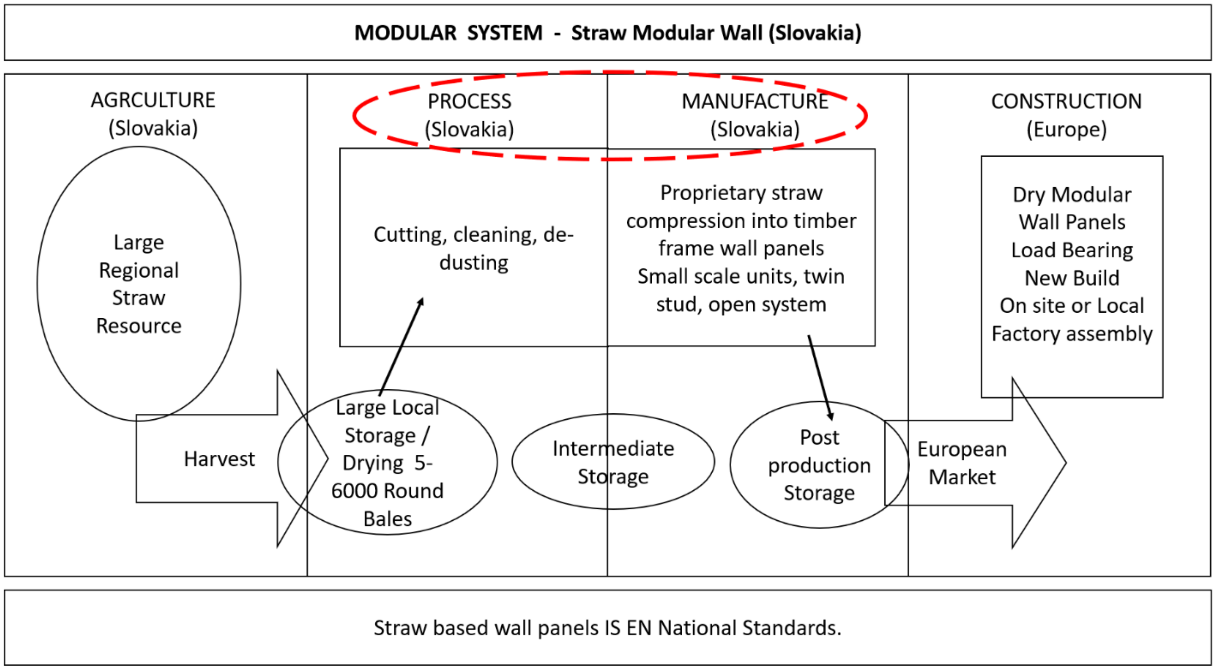

Figure 13: Showing high level supply chain mapping of straw based modular wall system manufacturer based on small module unit and use of automation in manufacture [Source Authors].

This case highlights the following key aspects; small module design for ease of handling and transport, strategic location to transport / shipping hubs, use of patented manufacturing technology, developing retrofit panel, use of secondary assembly factories, plans for multiple regional plants and further integration of automation,

5. Supply Chain Dynamics

This section presents an overview of key supply chain aspects and distinctives that emerged from the semi structured interviews and case study research discussed across four key stages of agriculture, process, manufacture and construction.

5.1. Agricultural Resources

Of the three agri-crops examined straw is the dominant and relatively massive resource, however all three resources are being utilised in a range of biobased constructions. Straw and miscanthus are harvested via conventional equipment and methods, whereas hemp requires some specialist harvesting equipment and processing. Crop resource type, and even variations in plant varieties, have impacts on processing, manufacture, and potential application with some differences in carbon profile and performance in use.

Manufacturers are securing their resources in a diversity of ways with different supply, transport and storage issues. While in general material and products are linked to regional resources, this is not determinant in all cases, with some manufacturers transporting resources significant distances related to supply availability and quality factors.

Resources are sometimes secured on open market directly at harvest, especially where there is significant resource availability, for example straw, or resources can be supplied under contract growing, with some examples of companies growing resources directly, e.g. for testing and trials in particular.

Transport and storage are handled in different ways depending on the resource, processing and manufacture. For example, some companies order on an as needs basis with farmers storing and supplying material, while others receive resources at harvest and must arrange often large-scale storage themselves.

5.2. Processing

Some processors / manufacturers can use resources direct from farm with zero to low processing, e.g. straw bales, but in most cases, there is some element of processing, either primary or secondary, in house or by third party.

Straw can be used direct from farm as bales but is also being processed for re-baling or as infill into modular systems or chipped and dust filtered, or fibre extracted for blow in straw applications or used to manufacture construction board / batts.

Hemp stems are typically processed to separate the fibre and shiv / chip, which may need additional dust filtering, with the fibre being applied mainly in quilt products or as an additive to other construction materials, and the shiv generally being the main ingredient in hempcrete infill or masonry blocks and being used in some hemp boards.

Processing may be done by specialist dedicated third party processors, e.g. hemp, which tends to require more specialist processing equipment and larger scale plant. There are also independent straw processors producing straw chips, however, some manufacturers, mainly straw based, are undertaking some level of in-house processing, primary and or secondary, both for product and modular systems.

Scale and type of processing varies and is relative to technology level, with low and low medium technology levels utilising simple and existing agricultural processing methods, while others require more specialist and large-scale technology.

Generally processing / manufacture is located relatively close to agricultural source, especially for straw given the widespread and disperse availability of same, but there are some examples of material being transported inter-regionally / internationally, for example French hemp shivs being imported into the UK and Italy. See Fig. (**14**) for example of large hemp processing plant in northern France.

Figure 14: Hemp processing facility showing hemp bales input/storage, hemp processing and fibre/shiv outputs. Planet Chanvre Northern France [Source Authors].

5.3. Manufacturing

There are a diversity of manufacturing approaches subject to material, product or system, with modular systems tending to manufacture on order, while materials and products tend to be manufactured in bulk ready for supply.

i) Straw Based Material and Products

While most straw bales are baled on farm, one company was found providing re-baling to specific characteristics, with additional straw chipping and filtering for blow in straw application.

Some manufacturers, both modular and product have specific proprietary processes, from filling and compressing straw into modular systems to pressing and forming straw fibres in board and batts, some involving binders and additives. See Fig. (**15**) showing examples of straw solutions

Figure 15: Showing range of straw based resource materials and products bales, straw chips (Straw Chips Ireland) and boards (VestaEco northern Poland) [Source Authors].

ii) Hemp Based Material and Products

Hemp shiv is typically processed for use in hempcrete infill within timber frame. Several manufacturers have developed proprietary binders for their shiv based 'hempcrete', often via proprietary additions to lime, for increased performance or faster drying.

Hemp blocks are generally manufactured from similar hemp lime mixes, in either bespoke or adapted block pressing and drying lines.

Hempcrete drying time has impacts on the manufacturing process notably for drying storage.

Hemp boards are typically manufactured from shiv in specialist process lines, involving pressing, some with binders and additives. Hemp batts and quilt are typically manufactured from fibre, sometimes combined with other materials, in large scale / specialist plant lines. See Fig. (**16**) for examples of Hemp solutions.

Figure 16: Showing range of hemp based resource materials and products (shiv, hempblocks, and hemp fibre batts). Senini-Tecno Canapa Northern Italy [Source Authors].

iii) Modular Systems

Modular system manufacture is generally akin to timber frame manufacturing lines with assembly beds or tables for horizontal work and working areas for vertical module work, with gantry cranes for lifting internally. Biobased insulation infill is applied in a range of ways including manual, infill from hopper, compression and blow in, with wet material requiring drying time and storage space. Modular systems are mainly wall components but with some roof and floor modules. Some manufactures are moving toward automation in assembly. See Fig. (**17**) for examples of two biobased modular systems facilities in France.

Figure 17: Showing straw based (above) and hemp based (below) biobased modular wall panel manufacturing facilities. Chênelet (straw) & Wall'Up Prefa (hemp) Northern France [Source Authors].

5.4. Storage and Transportation

Transport and storage needs vary subject to nature of resource and processing / manufacture, with a diversity of input and output storage requirements.

All material and products have different storage and transport issues. For those supplying bulk low processed material such as hemp shiv or straw chips they tend to be stored in large hoppers for later application or bagging. Hemp block manufacturing needs drying storage and later plastic wrapping and stacking on pallets with additional post completion storage often sheltered. Similarly post completion packaging and storage is required for boards, batts and quilts. Most materials and products are transportable via pallets.

Modular system storage is usually managed by on demand manufacture. Two key storage and transport issues were i) wet or dry materials impacting on drying times and storage and ii) module size with small module units facilitating simpler storage / stacking and transport, compared to larger (open or closed cell) systems which could not be stacked, and including use of local second stage assembly locations for larger and closed panel formation, often close to site.

5.5. Construction Application

Construction application of materials, products and systems is also diverse but with a significant bias on timber frame application, and a notable development in modular applications, notably for wall systems.

Most materials and products are applied in timber frame constructions, including all modular systems, however there are also medium weight masonry block products being utilised, generally nonloadbearing in post and beam constructions. Most materials and products are applied in new construction however there is some application and interest in retrofit application including from modular system manufacturers.

Another key distinctive feature is wet or dry manufacture or construction, of which there is diversity and variation. Hempcrete infill is applied wet on site and in factory for modular systems with the latter dry installed on site. There are also examples of straw products and modular systems being manufactured via a wet process but a dry product element being output for site application.

For further details on material, product and modular system types, characteristics and performances please refer to precursor Paper 1 [40].

5.6. Markets and Certification

Manufactures are supplying both regionally and across Europe, reporting some limitations and barriers around local / regional regulatory variation and transport costs.

Products are generally being sold and applied across Europe, with transport costs limits, and many manufacturers developing regional partner suppliers to trade through.

Modular manufactures are located both near to urban centres / regional markets and or to resource / processing or to transport / freight routes and international markets, the latter more typically for the small modules systems.

In all cases testing and certification are critical for market entry and expansion and most manufactures are attempting to quantify the carbon saving or storage aspect of their solutions.

For further details on certification and carbon profiling please refer to precursor paper 1 [40].

5.7. Diversity

Overall supply chains exhibited some broad commonality with significant diversity and customisation not only in resource type, harvesting processing, manufacture and construction application but also in relation to scale, sophistication (e.g. manual labour versus automation), standardisation / customisation, logistic and commercial strategy e.g. location and module size, market penetration and business expansion plans.

6. Summary - Key Findings

Fifty-seven companies active in biobased construction from agri-crops (straw miscanthus and hemp), were reviewed with semi structured interviews conducted with a representative sample toward mapping and analysis of supply chains with key integrated aspects noted as follows.

6.1. Crop Utilisation

The utilisation of a particular crop is a key determinant in the supply chain and may be impacted by various factors including resource type and availability, dedicated use crop or waste / by product crop e.g. straw, land - soil condition, processing availability, material / product output and intended construction application.

6.2. Processing / Manufacture

Processing and manufacture for construction may be dictated by several factors including resource type and availability, type of material / product and construction application, (which will impact on type and level of processing - simple to complex), weather in house or third party, or if primary or secondary process are required.

6.3. Construction Application

The actual and specific application of these agri-crop resources in construction will have downstream impacts across the supply chain with specific crop, harvesting, processing and manufacture impacts, taking resource properties and potential performance into account.

6.4. Transport, Handling and Storage

Transport, handling and storage aspects are key considerations across all stages of the supply chain, impacting the design and nature of the product itself and its costs and carbon profile with issues of storage locations and stages, space, shelter, internal or external, manual or assisted or full powered lifting (cranes, hoists etc.), stacking and transport modes being some key factors.

6.5. Certification and Testing

These agricultural resources are being applied in a construction sector which has very specific construction performance requirements, with stringent and sophisticated testing and certification standards for building regulation approval, hence testing and certification are key to market entry.

6.6. Market

The costs and extent of such testing is a key factor in product development and market entry / expansion with some complexity and barriers reported around variations in testing and performance requirements across Europe, e.g. for fire.

6.7. Carbon Profile

Along with various thermal and moisture regulating advantages claimed, most companies are emphasising the significant carbon savings potential from their products with many undertaking some form of life cycle carbon assessments on same.

While markets for carbon trading of construction products are not yet developed there is significant interest in this area from parties along the supply chain with potential as an additional revenue stream.

7. Conclusion

This research has found that agricultural crops, straw, miscanthus, and hemp, are being commercially utilised within diverse supply chains, producing various biobased materials, products, and modular systems for construction application in Europe and beyond.

The findings demonstrate innovation and commercial development in biobased construction solutions with key supply chain aspects and dynamics identified and discussed via case study comparative analysis and overall synthesis.

Supply chains themselves were noted to be diverse, tailored and related to specific agri-crop resource type and availability, processing location and functionality, possible needs for secondary or in house processing and a range of manufacturing approaches, technologies and complexity levels, which are dictated by resource properties and construction performance requirements (moisture, thermal, fire etc.), which themselves are subject to stringent and specific testing and regulatory standards, with significant differences in scale, mode, market, customisation, complexity and sophistication.

Further research could support the expansion and optimization of these supply chains and construction solutions, which could bring significant benefits in terms of carbon reduction, circularity, and reduced environmental impact, by optimising agricultural resources, streamlining processing and manufacturing, improving in use performance, and removing barriers - notably harmonising regulatory / testing requirements for wider market penetration.

Conflict of Interest

No potential conflicts of interests are reported by the authors

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Author’s Contributions

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

Paula Gallego Barril: Research assistant; supporting in investigation, analysis, data collation, visualisation, and bibliography.

References

[1] UNEP. 2023 Global Status Report for Buildings and Construction: Beyond foundations - Mainstreaming sustainable solutions to cut emissions from the buildings sector. United Nations Environment Programme; 2024 Mar. Available from: https://wedocs.unep.org/20.500.11822/45095 (Accessed: Sept. 13, 2024).

[2] García C, Caro J, Gallo G, Tonini F. Techno-economic and environmental assessment of construction and demolition waste management in the European Union. Luxembourg: Publications Office of the European Union; 2024, JRC135470. https://data.europa.eu/doi/10.2760/721895

[3] European Comission. The story of the von der Leyen Commission: The European Green Deal. 2024.

[4] European Commission. In focus: Energy efficiency in buildings. Brussels: 17 February 2020. Available from: https://commission.europa.eu/news/focus-energy-efficiency-buildings-2020-02-17_en (Accessed: June 2024).

[5] European Commission. Circular Economy: Principles for building design. 20 February 2020. Available from: https://ec.europa.eu/docsroom/documents/39984 (Accessed: Sept. 13, 2024).

[6] Benachio GLF, Freits M do CD, Tavares SF. Circular economy in the construction industry: a systematic literature review. J Clean Prod. 2020; 260: Article ID: 121046. https://doi.org/10.1016/j.jclepro.2020.121046

[7] Joensuu T, Edelman H, Saari A. Circular economy practices in the built environment. J Clean Prod. 2020; 276: Article ID: 121046. https://doi.org/10.1016/j.jclepro.2020.124215

[8] European Commission. A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives. Brussels: 14 October 2020. Available from: https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52020DC0662.

[9] European Commission. European Green Deal: Commission proposes to boost renovation and decarbonisation of buildings. Brussels: 15 December 2021. Available from: https://ec.europa.eu/commission/presscorner/detail/en/IP_21_6683.

[10] European Commission. A new Circular Economy Action Plan For a cleaner and more competitive Europe. Brussels: Mar 2020.

[11] Gov.ie. Climate Action Plan 2024. Ireland: Department of the Environment, Climate and Communications; 20 December 2023. Available from: www.gov.ie

[12] Gov. ie. Bioeconomy Action Plan 2023-2025 version 2.0. Ireland: Department of the Environment, Climate and Communications and the Department of Agriculture, Food and the Marine; 2023 Oct.

[13] IGBC. Building a Zero Carbon Ireland, 2022. Available from: https://www.igbc.ie/wp-content/uploads/2022/10/Building-Zero-Carbon-Ireland.pdf (Accessed: May 30, 2024).

[14] IGBC. Building a Zero Carbon Ireland: Government Policy Scorecard. 2024. Available from: https://www.igbc.ie/wp-content/uploads/2024/02/Policy_Scorecard_Summary_FINAL.pdf (Accessed: May 30, 2024).

[15] Curran MA. Biobased Materials. In: Kirk-Othmer Encyclopedia of Chemical Technology. Wiley; 2010. p. 1-19. https://doi.org/10.1002/0471238961.biobcurr.a01

[16] Bourbia S, Kazeoui H, Belarbi R. A review on recent research on bio-based building materials and their applications. Materials for Renewable and Sustainable Energy. Mater Renew Sustain Energy. 2023; 12(2): 117-39. https://doi.org/10.1007/s40243-023-00234-7.

[17] Motamedi S, Rousse DR, Promis G. The evolution of crop-based materials in the built environment: a review of the applications, performance, and challenges. Energies. 2023; 16(14): 5252; https://doi.org/10.3390/en16145252

[18] UNEP. Building Materials and the Climate: Constructing a New Future. Report. 12 September 2023.

[19] Keena N, Raugei M, Lokko ML, Aly Etman M, Achnani V, Reck BK, *et al*. A Life-Cycle Approach to Investigate the Potential of Novel Biobased Construction Materials toward a Circular Built Environment. Energies. 2022; 15(19): 7239. https://doi.org/10.3390/en15197239

[20] Chen L, Zhang Y, Chen Z, Dong Y, Jiang Y, Hua J, *et al*. Biomaterials technology and policies in the building sector: a review. Environ Chem Lett. 2024; 22: 715-50. https://doi.org/10.1007/s10311-023-01689-w

[21] Global Energiesprong Alliance. Circular Reno-Interrreg NW Europe. 2023. Available from: https://circularreno.nweurope.eu/ (Accessed on 2024 Jun 3).

[22] Yin RK. Case study research: design and methods, 5th ed. Applied Social Research Methods Series. SAGE Publications; 2009.

[23] John W. Creswell. Research Design: Qualitative, Quantitative, and mixed methods approaches. 4th ed. SAGE Publications; 2009.

[24] Koh CH (Alex), Kraniotis D. A review of material properties and performance of straw bale as building material. Constr Build Mater. 2020; 259: 120385. https://doi.org/10.1016/j.conbuildmat.2020.120385

[25] Zhang L, Larsson A, Moldin A, Edlund U. Comparison of lignin distribution, structure, and morphology in wheat straw and wood. Ind Crops Prod. 2022; 187: 115432. https://doi.org/10.1016/j.indcrop.2022.115432

[26] Cascone S, Rapisarda R, Cascone D. Physical properties of straw bales as a construction material: A review. Sustainability. 2019; 11(12): 3388; https://doi.org/10.3390/su11123388

[27] Department of Agriculture, Food and the Marine. Straw incorporation measure (SIM). Ireland: 2022. Available from: https://www.gov.ie/en/service/f16b22-basic-payment-scheme/

[28] European Commission. Cereal production in the EU (ha). 2023. Available from: https://ec.europa.eu/eurostat/databrowser/view/apro_cpsh1__custom_11419163/default/map?lang=en (Accessed on May 17 2024).

[29] European Commission. Cereal production in the EU (tonnes). 2022.

[30] Kaminski KP, Hoeng J, Goffman F, Schlage WK, Latino D. Opportunities, Challenges, and Scientific Progress in Hemp Crops. Molecules. 2024; 29(10): 2397. https://doi.org/10.3390/molecules29102397

[31] Kaur G, Kander R. The Sustainability of Industrial Hemp: A Literature Review of Its Economic, Environmental, and Social Sustainability. Sustainability. 2023; 15(8): 6457. https://doi.org/10.3390/su15086457

[32] Auriga R, Pędzik M, Mrozowski R, Rogoziński T. Hemp Shives as a Raw Material for the Production of Particleboards. Polymers. 2022; 14(23): 5308.

[33] Martínez B, Bernat-Maso E, Gil L. Applications and properties of hemp stalk-based insulating biomaterials for buildings: review. Materials. 2023; 16(8): 3245. https://doi.org/10.3390/ma16083245.

[34] European Commission. Hemp production in the EU (tonnes). 2023.

[35] European Commission. Hemp production in the EU (ha). Available from: https://ec.europa.eu/eurostat/databrowser/view/apro_cpsh1__custom_11419051/default/map?lang=en (Accessed on 17 May 2024).

[36] Eschenhagen A, Raj M, Rodrigo N, Zamora A, Labonne L, Evon P, *et al*. Investigation of miscanthus and sunflower stalk fiber-reinforced composites for insulation applications. Adv Civ Eng. 2019; Article number 9328087. https://doi.org/10.1155/2019/9328087

[37] Shavyrkina NA, Budaeva V V., Skiba EA, Gismatulina YA, Sakovich G V. Review of current prospects for using miscanthus-based polymers. Polymers. 2023;15(14): 3097. https://doi.org/10.3390/polym15143097

[38] Moll L, Wever C, Völkering G, Pude R. Increase of Miscanthus cultivation with new roles in materials production—a review. Agronomy. 2020; 10(2): 308. https://doi.org/10.3390/agronomy10020308

[39] Lewandowski I, Clifton-Brown J, Trindade LM, Van Der Linden GC, S.chwarz KU, Müller-Sämann K, *et al*. Progress on optimizing miscanthus biomass production for the european bioeconomy: Results of the EU FP7 project OPTIMISC. Front Plant Sci. 2016; 7: Article1620. https://doi.org/10.3389/fpls.2016.01620

[40] Daly P, Barril PG. Agricultural Crops Biobased Materials in Construction – A State of Play of Commercial Solutions in Europe. Int J Archit Eng Technol. 2024; 17-35. https://doi.org/10.15377/2409-9821.2024.11.2

[41] Beamon BM. Supply chain design and analysis: Models and methods. Int J Prod Econ. 1998; 55(3): 281-94. https://doi.org/10.1016/S0925-5273(98)00079-6

[42] Piennar WJ. Introduction to business logistics. Southern Africa: Oxford University; 2009.

[43] von Bertalanffy L. General systems theory: Foundations, developments, applications (Revised edition). Vol. 6, New York, NY: George Braziller; 1968.

[44] Janvier-James AM. A new introduction to supply chains and supply chain management: definitions and theories perspective. Int Bus Res. 2012; 5(1): 194-207. https://doi.org/10.5539/ibr.v5n1p194

[45] Gardner JT, Cooper MC. Strategic supply chain mapping approaches. J Bus Logist. 2003;24(2): 37-64. https://doi.org/10.1002/j.2158-1592.2003.tb00045.x

[46] MacCarthy BL, Ahmed WAH, Demirel G. Mapping the supply chain: Why, what and how? Int J Prod Econ. 2022; 250: 108688. https://doi.org/10.1016/j.ijpe.2022.108688

[47] Construire en Chanvre. Référentiel label qualité « Chanvre Bâtiment ». 2017.

Appendix 01: List of companies sourced and assessed, including those manufacturing materials, products and modular panels.

COMPANY NAME	WEBSITE
ADAPTAVATE	www.adaptavate.com
AGROCHANVRE	www.agrochanvre-ecoconstruction.com
BALABOX	www.bala-box.com
BIOFIB	www.biofib.com
CANHAMOR	www.canhamorhemp.com
CANNABRIC	www.cannabric.com
CAPAROL	www.caparol.de
DUNAGRO HEMP GROUP	www.dunagro.nl
EAST YORKSHIRE HEMP	www.eastyorkshirehemp.co.uk
ECOCOCON	www.ecococon.eu
ECOINSUL	www.ecoinsul.eu
ECOPAJA	www.ecopaja.com
EDILCANAPA	www.edilcanapasrl.it
EKOLUTION	www.ekolution.se
EKOPANELY	www.ekopanely.cz
ERTHLY	www.erthly.co.uk
EUROCHANVRE	www.eurochanvre.eu
EXIE	www.exih2.be
FBT ISOLATION	www.fbt-isol.com
GREEN CORE HOMES	www.greencorehomes.co.uk
HEMPFLAX	www.hempflax.com
HEMSPAN	www.hemspan.com
INDINATURE	www.indinature.co
ISOCELL	www.isocell.com
ISOHEMP	www.isohemp.com
ISO-STROH	www.iso-stroh.ch
KINGSPAN	www.kingspan.com
KOBE	www.kobe-cz.eu
LA CHANVRIERE	www.lachanvriere.com
LORENZ	www.lorenzsysteme.de
MISCANCELL	www.miscancell.nl
MISCANTHUS-BUSCHERITZ	www.miscanthus-buscheritz.de
MODCELL	www.modcell.com
MODULINA	www.modulina.lt
NATURAL BUILDING SYSTEMS	www.naturalbuildingsystems.com
NAWARRO	www.nawaro.ch

NSPS	www.npsp.nl
OKAMBUVA COOP	www.okambuva.coop
PLANETE CHANVRE	www.planetechanvre.com
PREFAB STROBOUW	www.prefabstrobouw.nl
RICE HOUSE	www.ricehouse.it
RMT INSULATION	www.rmt-nita.es
SAINT ASTIER	www.saint-astier.com
SCHöNTHALER	www.schoenthaler.com
SENINI-TECNOCANAPA	www.tecnocanapa-bioedilizia.it
SONNENKLEE	www.sonnenklee.at
STRAMEN.TEC	www.stramentec.com
TECHNICHANVRE	www.technichanvre.com
THERMAFLECCE	www.thermafleece.com
TRADICAL/WEBER	www.fr.weber/en/tradical-hempcrete
VESTAECO	www.vestaeco.pl
VICARIUS CANNA	www.vicariuscanapa.it
VIEILLE MATERIAUX	www.vieille-materiaux.com
WALL UP	www.wallup.fr