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Biobased Construction from Agricultural Crops: Paper 1 - A State of Play of Commercial Solutions in Europe

Patrick Daly* and Paula G. Barril

School of Architecture Building and Environment, Technological University of Dublin, Dublin, Ireland

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ABSTRACT

In response to environmental concerns and the global warming issue in particular there is a growing drive to decarbonise the building sector and transition it to more circular practices.

Biobased construction materials, products and systems are an important low carbon and circular strategy as they can enable low to negative carbon construction and have strong circularity advantages notably being able to enter the bio cycle, using renewable, low to zero toxic resources and provide a range of other performance benefits, including moisture and vapour regulation.

This novel research presents a unique state of play on the commercial application of biobased construction from selected agricultural crops, straw, miscanthus and hemp, focused on the European context. A desk-based review of known biobased material producers and manufacturers is undertaken, supplemented with semi structured interviews and site visits, to provide a comprehensive overview of the sector and detailed account of the types of biobased materials, products and systems that are being applied in buildings across Europe and beyond.

The findings show that a diversity of agricultural crops are being utilised at different process, manufacture and construction technology levels, providing a range of tested and certified materials and products for application in mainly timber frame construction, but also some masonry solutions, and a growing number of modular systems. These operate in a diversity of supply chains and are being applied in a wide range of building types, both domestic and non-domestic, including multi story and complex buildings.

*Corresponding Author
Email: patrick.daly@tudublin.ie
Tel: +(353) 012206814

1. Introduction

This section presents an introduction to the research context, decarbonisation and circularly challenges, biobased construction and the research approach and methods.

1.1. Context

The building and construction sector has a significant environmental impact consuming some 34% of global energy demand and producing 37% of energy and process-related carbon dioxide emissions [1]. The sector also outputs significant construction and demolition waste (CDW), representing for example some 40% of all waste generated within the European Union, [2].

Given the environmental impacts and economic significance of the sector, Europe has directed substantial policy and legislative efforts towards enhancing the sustainability [3] and energy efficiency of the building stock [4], and more recently, sought to transition the economy and building sector towards more circular practices [5], motivated by the construction sector's high resource intensity and waste generation [6, 7].

Significant among Europe's suite of policy and legal measures are; the renovation wave [8], and the European Union Green Deal [9], aiming to decarbonize the existing stock, improve energy efficiency, promote renewable energy and reduce and recover construction waste, and the Circular Economy Action Plan, which promotes circularity principles for construction products [10].

The UK and Ireland are also seeking to decarbonise the sector, through the UK Clean Growth Strategy [11], and the Irish Climate Action Plan [12], with Ireland also introducing a Circular Economy Act [13], and the UK and Irish Green Building Councils developing frameworks and roadmaps to support decarbonisation in the building sector [14-16].

1.2. Biobased Construction

Biobased materials generally refer to those that derive from living matter – biomass, occurring naturally or synthesised from same [17]. Within the construction sector the principle resources for biobased materials derive mainly from agriculture and wood industry and are used in a diversity of construction applications. While timber is one of the most common biobased materials used in construction, there is a wide 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 [18].

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 [19].

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 constructions, crop-based biomass constructions can result in even lower carbon emissions [20, 21].

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 [22].

While the potential adoption of crop-based biomaterials remains relatively untapped [19], this research, on the emerging commercial applications of argi-crop materials in construction, shows evidence of biobased construction solutions overcoming challenges and barriers and being applied in mainstream construction with commercial viability.

1.3. Research Approach & Methods

This innovative research was undertaken to provide needed insights and knowledge on the state of play of commercial development of key agricultural crops (straw, miscanthus and hemp) into biobased construction materials and solutions within Europe. The research was conducted by Irish research partners of the Circ Reno project, an EU Inter-regions project seeking to promote biobased construction supply chains from agricultural crops and demonstrate application in social housing retrofit [23], in order to provide a synthesis of contemporary European commercial biobased construction applications toward supporting similar solutions and supply chain developments in Ireland.

The study examined the extent and scope of commercial application of straw, miscanthus and hemp crops in biobased construction in Europe, asking what materials, products and systems are being produced and manufactured, what are their key characteristics and performances and how are they being applied in construction, and comprised several research approaches and methods, principally qualitative as follows;

- Scoping literature review to establish context, key drivers and overview of biobased construction.
- A detailed (non-exhaustive) desk-based review of known suppliers, producers and manufactures was undertaken, and data collated and tabulated on material / product properties, applications and claimed benefits.
- A series of semi structured interviews were undertaken with a broad representative sample of a dozen companies representing actors along the supply chain, including growers, processors and manufactures, providing more detailed insights into the construction solutions and supply chain issues.
- This was supplemented by several field studies and site visits for more detailed insight into sector.
- All contributing to both detailed analysis of the materials, products and systems and synthesis overview of the sector.

See Fig. (**1**) below presenting a schematic overview of the research.

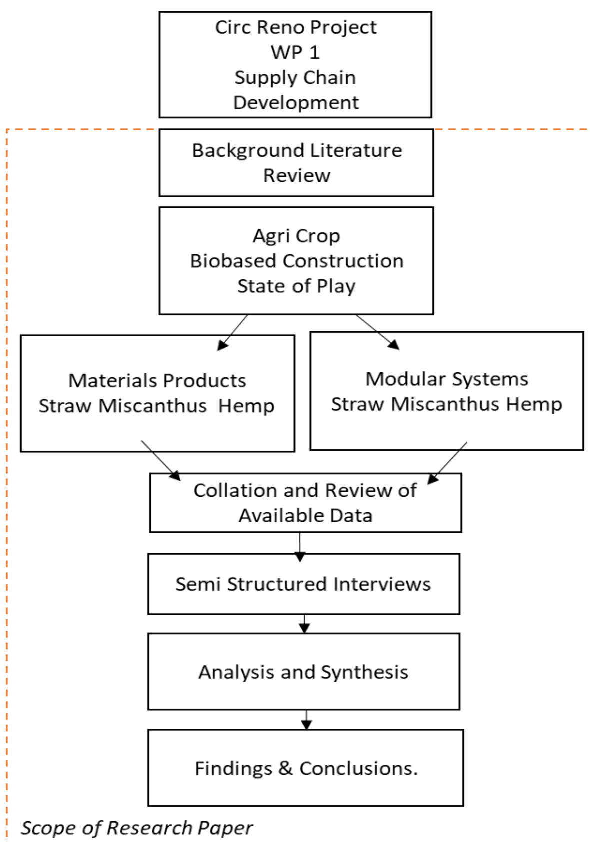

Figure 1: Schematic of the research scope and stages [Source Author].

The data arising from same was collated for both detailed comparative analysis of materials, products and systems, and an overall synthesis of the sector, with findings and results presented and discussed, contributing to contemporary knowledge on the state of play of biobased construction solutions from key agricultural crops in Europe.

The study represents research that is in progress and a ‘snapshot’ in time, and as such the representative companies are non-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 widespread application in Europe.

The study examines commercial activity by number and activity of companies and type of product and not by volume or tonnage of material.

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

2. Agricultural Crops in Biobased Construction

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

2.1. Agri Crop Resources

i) Straw

Straw is the leftover stalk after the grain has been harvested, and it can be sourced from various cereal plants such as wheat, maize, rice, barley, oats, rye and sorghum [24]. It consists mainly of cellulose, hemicellulose, and lignin [25] and having no nutritional value is mainly used for livestock bedding or as a biomass energy crop [26], or incorporating into soil to increase soil organic carbon levels [27]. Straw is a sustainable building material, being a renewable food by product, it sequesters carbon dioxide has low embodied energy during harvest and processing and can be re-applied or re-used at end of life or biodegrade [28].

Straw is available across Europe in huge quantiles with a diversity of cereals being grown across all countries representing some 50.69 million hectares [29] producing circa 270 million tonnes of cereal [30], with significant numbers of associated straw processors, for example producing chips for animal husbandry. Given the scale of the resource it is not surprising that straw bale for construction use is also significant across Europe with, for example, the EU Upstraw projects identifying around 287 suppliers of straw bale for construction across Western Europe [31].

ii) Hemp

Hemp (cannabis sativa L.) is a rapidly growing, multi yield industrial crop [32], utilising all the plant in numerous applications - seeds as a food source, animal feed, ingredient in cosmetics, or can be processed into oil, shives (hurds) and fibres from the stem are used for animal bedding, building materials, paper and textile, and the hemp flower is valuable for producing cosmetics and pharmaceutical products, including oils [33]. Decortication of the stalk results in long fibres, short fibres and shives [34]. The woody part (shives) located in the inner part of the stem, represents more than 50% of the plant’s weight, is typically considered waste in the hemp industry [35], but has application in animal bedding and construction.

Compared to straw, the hemp resource in Europe is minor but sufficient to supply hemp on industry scale, with EU land area used for hemp cultivation at 28,030 hectares in 2023 [29], producing circa 158,150 tonnes [36] with

France being the leading producer with more than 65% of EU production, followed by Germany (10%) and the Netherlands (7%), with smaller scale production happening across various European countries.

iii) Miscanthus

Miscanthus is a large perennial grass [37], requiring only one planting to remain productive for 20-25 years, thrives on marginal lands without needing special agricultural practices, can help remediate soils, and is non-invasive. Miscanthus is also a carbon-negative crop, and it builds an equal biomass volume both above and below ground [38]. Consisting of mainly cellulose, hemicellulose and lignin [39],, miscanthus has a wide range of core applications across various sectors, including energy, industrial biotechnology, the chemical industry, the pulp and paper industry, organic farming and construction [38].

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 [40].

2.2. Biobased Solutions Commercial Activity

i) Overview

Altogether (and ignoring farm direct supply of resources for construction application, such as straw bale) some 57 biobased companies were sourced and reviewed with 46 involved in the supply and manufacture of agricultural crop biobased materials and products and 15 utilising these resources in modular construction systems. Please see Appendix **03** for full list of companies sourced and reviewed.

Companies active in straw construction material and product supply are widespread including straw bale, blow in straw and other products manufactures of boards and batts, as well as modular systems using a diversity of straw application. While straw is the dominant resource, hemp-based companies active in manufacture of biobased material and products are numerically higher, with a dominant cluster around Western Europe – notably France, Germany and the Benelux countries, likely aided by proximity to large-scale resource availability, (however several companies were found to be utilising imported hemp resource) (Fig. **2**).

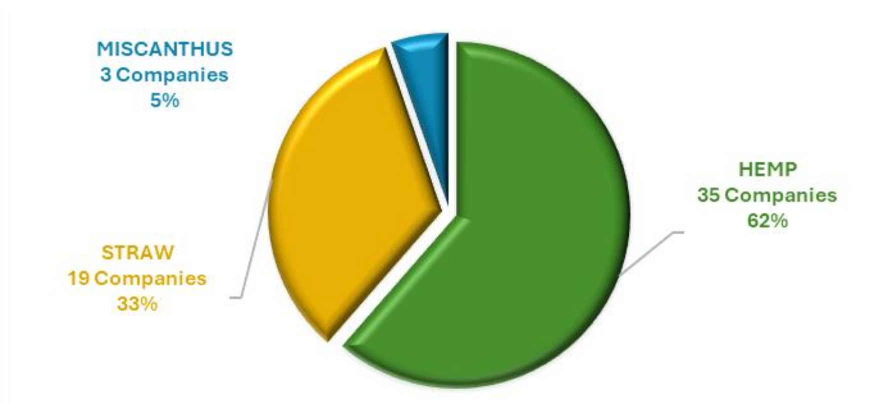

Figure 2: Companies involved in the manufacture of biobased materials, product and/or modular systems by resource type, straw, hemp, miscanthus (ignoring farm direct resources) [Source Authors].

ii) Materials and Products

Approx. 46 commercial companies were identified as engaged in the manufacture of biobased construction materials and products from agricultural crops - straw, miscanthus and hemp, with hemp companies being numerically dominant, with hemp companies primarily located in West, and straw in East, ignoring straw bale which is disperse (Fig. **3**).

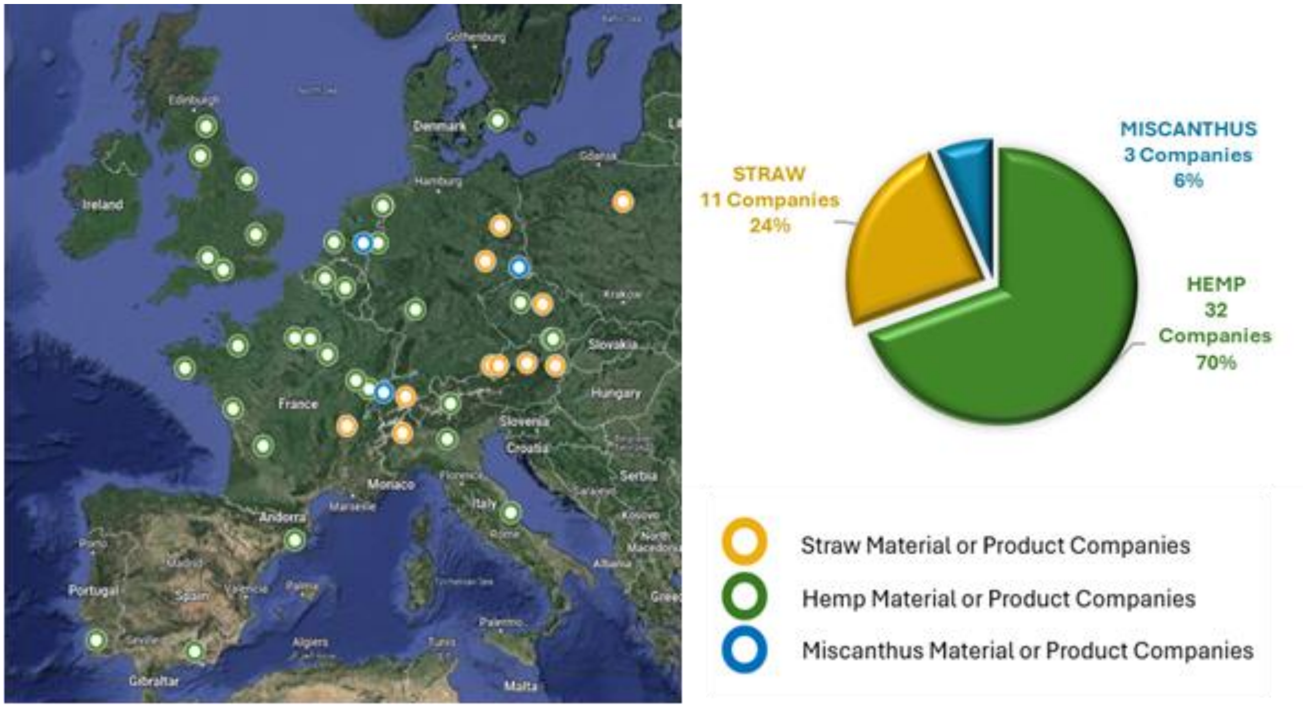

Figure 3: Companies active in supply of biobased materials and products across Europe, LHS - location map, RHS percentage chart, all by resource type [Source Authors].

iii) Modular Systems

Some 15 companies were noted to be engaged in the manufacture of modular systems from these agri-crops and in some cases using materials supplied by other companies, reported above. Some modular companies are operating regionally, most are exporting across the EU and some are planning additional manufacture capacity and plants (Fig. **4**).

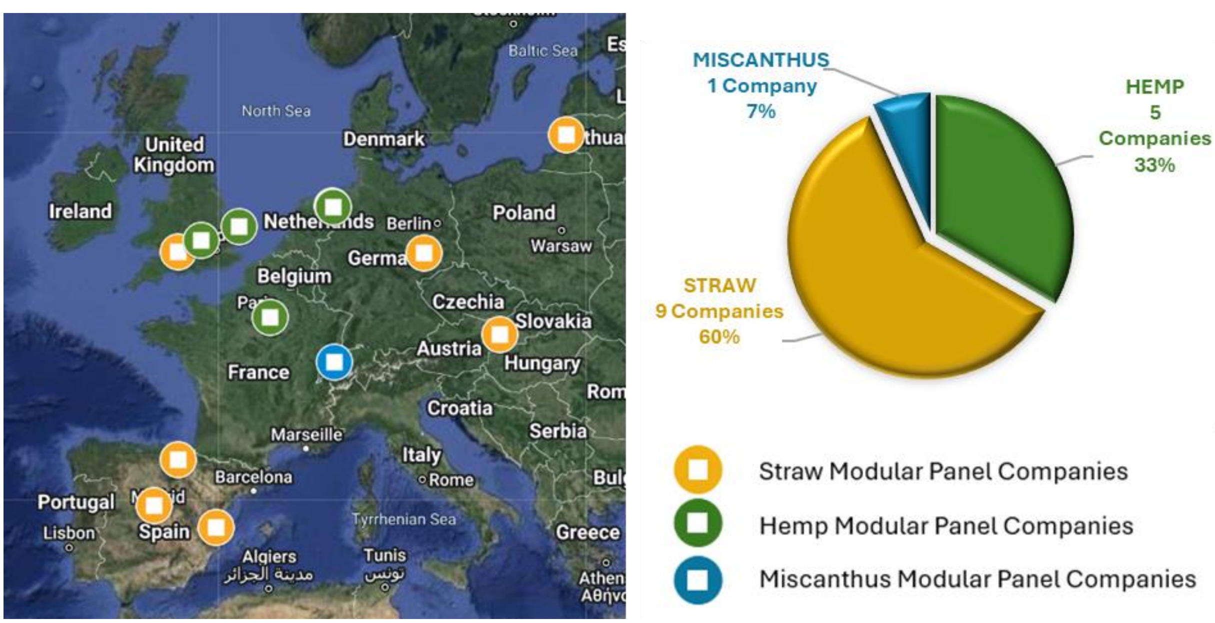

Figure 4: Companies active in supply of biobased modular systems across Europe - LHS location map , RHS percentage pie chart, all by resource type [Source Authors].

3. Materials and Products

This section presents an overview of companies engaged in the manufacture of biobased materials and products and a more detailed account their materials and products structured by broad technology – complexity levels, describing their key characteristics and performances.

Please see Appendix **01** for further details.

3.1. Overview

i) Hemp

Companies producing hemp related materials and products were numerically dominant, (circa 32) spread across both wet and dry applied solutions.

The 'wet' solution is a low – medium technology wet application of 'hempcrete', a composite of hemp shiv and a binder, typically lime, for infill in framed structures, either manually or sprayed.

A similar wet hemp lime mix is utilised in more specialist manufacture of medium technology level masonry block units producing dry, mainly non load bearing blocks.

Several hemp companies were noted to be producing a range of dry applied medium technology level - boards, batts and quilts for application in framed construction.

ii) Straw

Companies utilising straw resources were also significant representing approx. 11 companies producing a range of materials and products at different technology levels mainly dry solutions for timber frame application, including use of straw bale, chopped straw for blow in and some producing boards and batts.

iii) Miscanthus

Companies utilising miscanthus were the minority with only one product manufacturer being found, (boards), however there were two examples of miscanthus processing companies supplying extracted resources (from miscanthus) into the construction sector notably, shivs or chips of various dimensions, lignin for use in tarmac and cellulose being developed for possible insulation product.

See Figs. (**5** and **6**), for a high-level overview of the number of companies and types of materials and products being manufactured.

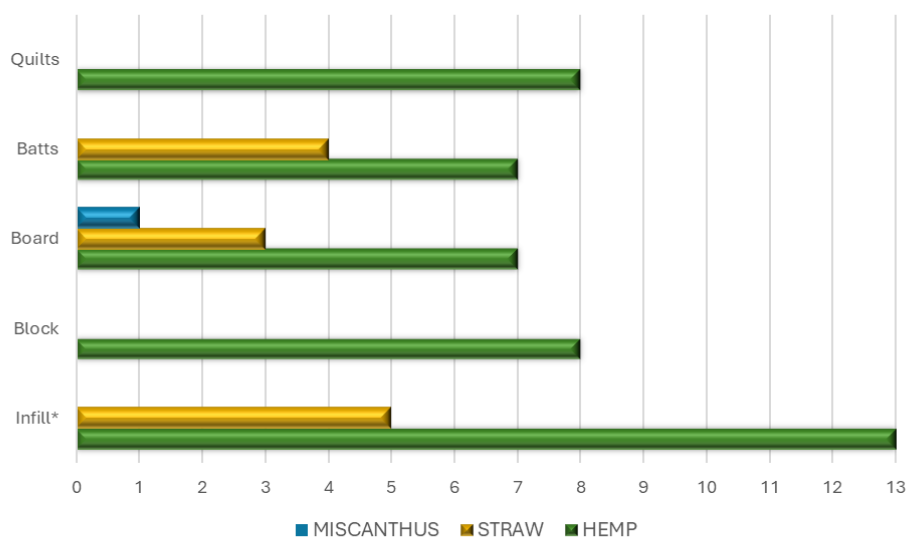

Figure 5: Showing number of companies in Europe producing biobased materials and products from straw, hemp and miscanthus resources. *Note: *Infill materials considered include hemp shives, blow-in straw and two specialist companies actively supplying bales as a product* [Source Authors].

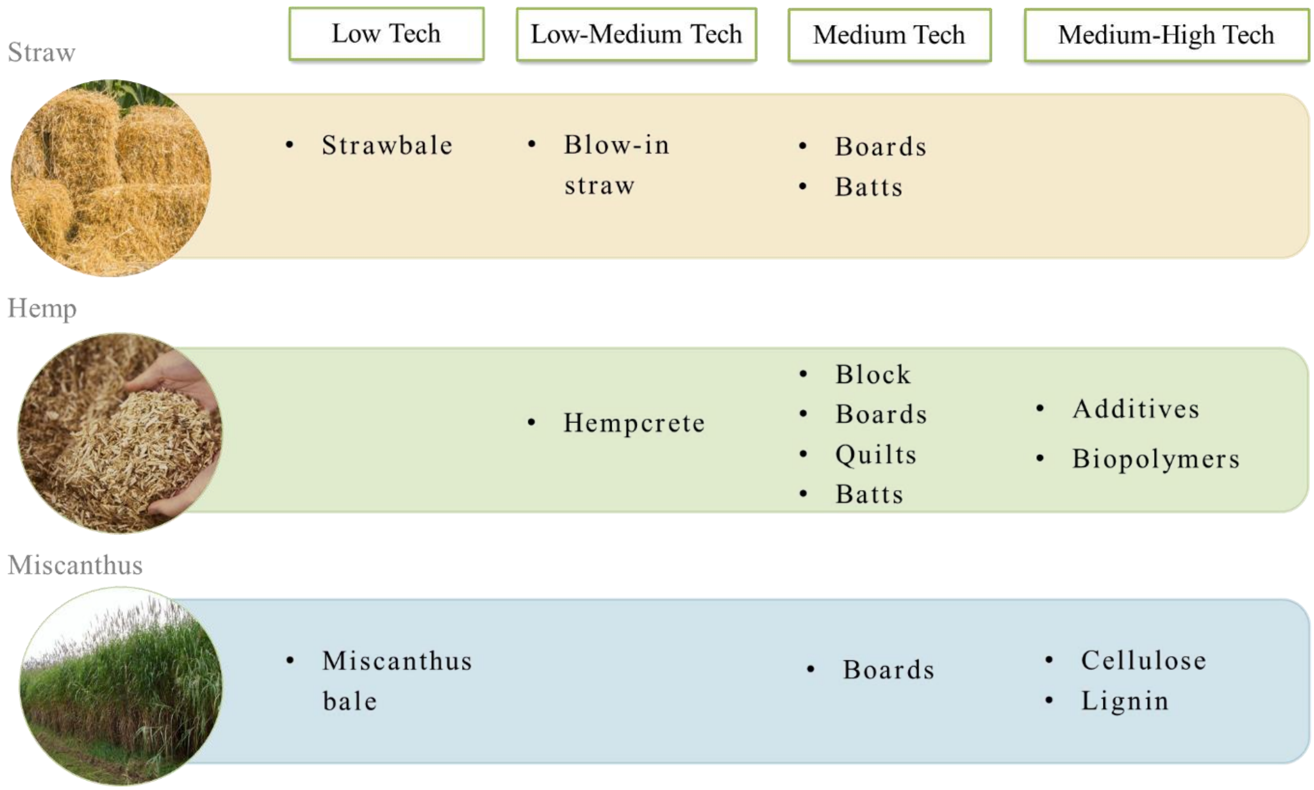

Figure 6: Presents a summary chart of the type of application of agri-crop biobased materials and products under broad technology – complexity levels [Source Authors].

3.2. Low Technology Level

Low technology applications, herein being categorised as minimal processing (close to raw harvested state), zero to minimal manufactures and simple construction methods, comprised use of straw and miscanthus bale applied in timber frame construction.

Most applications of these materials are purchased direct from farms or via straw bale building companies, with two specialist companies found actively supplying bales as a product, and with several utilising bale or blown chips within modular systems.

Straw bales are typically formed at harvest time with some dimension variations. relative to process and machinery utilised, at 460 to 510mm width by 357 to 380mm height by 800 to 1200mm length [28].

They are mainly applied as non-load bearing insulative infill in new build timber frame constructions, principally walls, but with examples in floors and roofs, mainly in one off dwellings but with some non-domestic case examples.

Some construction companies have undertaken rigorous testing of material properties notably under European Assessment Document (EAD), which sets testing and performance standards for straw bale construction [41], securing ETA's European Technical Assessment Certification (ETA) and European production quality certification - European Conformity (CE) with an example showing performance of unfinish straw bale of Fire (Class E), thermal conductivity at 90° to stalk orientation 0.043 W/(mK) with a density of circa 100kg/m^3 and positive moisture absorption and diffusion values [42].

From tests of clay and lime plastered strawbale wall systems presents Class B-s1,d0 reaction to fire (BS EN 13501-1:2008) and 120 to 135 minutes resistance to fire without failure REI 120-135 (BS 476-7:1997) [28].

No carbon sequestration data was found however the Environmental Product Declaration (EPD) for straw bale as insulation material in UK reports carbon emissions across the whole lifecycle, at density of 100kg/m^3 being 14.12 kgCO_2eq/m^3 and the biogenic carbon being 129.25kgCO_2e/m^3 [43] (Fig. **7**).

Figure 7: Showing examples of straw application of straw bale as infill wall in timber post and beam construction. Architecture barchi Belgium [Source Author].

3.3. Low – Medium Technology Level

Low- Medium Technology level solutions, being broadly classified as low to moderate level of processing, manufacture and construction methods, included a range of material resources and applications notably hempcrete and blow in straw.

i) Hempcrete

Hempcrete is a simple composite of hemp shiv (the plant stem after fibre separation) mixed with a binder, typically lime and water, which is hand or machine mixed and applied in a timber frame structure either by manual infill or spray application. The simplicity of the solution has leant itself to domestic self-builders and small contractors, however there are growing applications of the material by commercial contractors in larger scale building projects including non-residential [44]. There is no harmonised standards or EAD for 'hempcrete' construction however the Construire en Chanvre, an association promoting and certifying hemp production and application in France has developed specification guidance for the manufacture and application of the material and biocomposite, including shiv sizes, fibre and dust limits, and proprietary binders [45].

Fourteen hemp shiv manufactures have been found across Europe. Although most shiv manufactures test and certify their products with a specific lime binder, in France, there is also a list of approved aggregate binders, in line with the Construire en Chanvre guidelines [45].

An example of key performances from a hempcrete mix of 28% binder, 25% shiv, 1% probiotics and 46% water, applied at a density of 230 kg/m^3 can achieve a thermal conductivity value of 0.053 W/(mK) with a reaction to fire in a thickness of 300mm when lined with gypsum fibre panels, of A1 En 13501-1 Class I, and absorbing 104 kg CO_2eq./m^3 [46] (Fig. **8**).

ii) Blow in Straw

Blow in straw involves some minor processing of harvested straw, typically chopping and sieving of straw to remove dust, (with some using additives) to create a simple 'blow in' insulative fibre straw material, which is typically applied into framed structures, (wall, roof and floor), both new build and retrofit, including in modular systems.

Figure 8: Showing hempcrete spray applied to existing masonry wall in rural house renovation. Senini-Tecno Canapa northern Italy [Source Author].

Several companies have manufactured to requirements under EAD 040138-00-1201 for in-situ formed loose fill thermal and/or acoustic insulation products made of vegetable fibres, with one example producing straw fibres lengths of 30mm, maximum fibre width of 5mm, fine particle content <1mm 5-15% content by weight as well as the moisture content inferior to 15% by weight [47].

When applied via standard blowing technology example performance ranges are densities of 105-115 kg/m^3 for roofs, and 115 to 140 kg/m^3 for walls [48]. With example thermal conductivity values of 0.057 W/mK at density 100 kg/m^3 and achieving Fire Class E when tested to EN 13501-1:2009 under direct flame exposure [47].

Several companies have ETA's for blow in straw and CE Marking however no EPD's were found.

3.4. Medium Technology Level

At medium technology level, broadly defined as a medium level of processing with medium manufacturing and construction methods, the raw materials are being both processed and manipulated in more advanced ways to produce specific products, rather than materials, notably in two broad subcategories of i) masonry blocks and ii) boards, batts and quilts for timber frame construction.

i) Masonry Block

The predominant masonry block product is manufactured from lime based hempcrete mixtures, generally for non-load-bearing applications, with some solutions designed for integration to post and beam.

The mixtures are generally similar to hempcrete but with different mix proportions, mixed with either hydraulic or hydrated lime with some manufacturers using additives for advanced drying. The wet hempcrete is typically pressed into moulds achieving example higher densities of circa 330kg/m^3 [46], 310-360kg/m^3 [49] and manufactured to a range of block sizes.

Performance values relate to mixes and density with one example (with plaster finish), having thermal conductivity values 0.07 W/mK, achieving a Fire Class B,s1,d0 according EN 13501-1 and absorbing 44.2 kg CO_2eq./m^3 [50] and another manufacturer reporting thermal conductivity values of 0.076 W/mK, Fire Class B,s1,d0 according EN 13501-1 (without plaster), and absorbing 75.4kg CO_2eq/m^3 [51] (Fig. **9**).

Figure 9: Showing hemp shives added to lime / water binder to manufacture hempcrete masonry blocks. Senini-Tecno Canapa northern Italy [Source Author].

ii) Boards / Batts / Quilts

A diversity of boards, batts and quilts are being manufactured mainly from straw or hemp, with one example from miscanthus.

Boards

Boards are typically higher density and comprise a range of materials, mixes and performances. A wide variety of boards made from straw or hemp have been identified, including those for drywall applications, with different particle sizes and components e.g. clay is added to hempcrete to enhance humidity regulation.

High Density: These boards are mainly hemp based and have densities ranging from 350 to 1000 kg/m^3 and thermal conductivity values between 0.09 and 0.165 W/mK. The available dimensions are approximately 1200mm in length by 600mm in width, with thicknesses varying from 10 to 60mm.

Light Density: A lighter range of boards, primarily composed of fibres rather than shivs, are available for both straw and hemp, with an example straw board density of approximately 320 kg/m^3 and a thermal conductivity of 0.057 W/mK [52] and hemp boards densities between 85-140 kg/m^3 and a thermal conductivity of 0.38 - 0.045 W/mK. One company producing a miscanthus board, manufactures a high and low density board subject to binder type with significant range of density and conductivity, 125 kg/m^3 - 320 kg/m^3 and 0.072 W/mK - 0.045 W/mK respectively.

Some of these manufacturers have obtained an ETA as part of an EAD 040005-00-1201 certification for “Factory-made thermal and/or acoustic insulation products made of vegetable or animal fibres” [53] and some of these boards have CE marking.

Batts and Quilts

Some four companies are manufacturing straw batts only and approximately fourteen companies producing both batts and quilts with hemp.

The main components of these batts are hemp or straw fibres, with added polymer binders and fire retardants such as sodium carbonate. Hemp or straw batts typically have a density of 50-70 kg/m^3 and a thermal conductivity of 0.037 - 0.041 W/mK.

Hemp quilts offer similar thermal conductivity but have a lower density range 25-40 kg/m^3, and are available in mat and roll forms. Both lighter boards and batts are available in standard dimensions of 600 by 1200mm and come in a wide range of thicknesses, from 40 to 200mm.

Some of these manufacturers have obtained an ETA as part of an EAD 040005-00-1201 certification for "Factory-made thermal and/or acoustic insulation products made of vegetable or animal fibres" [53].

Some products carry a CE marking, BBA certificate, and or EPDs. For example, for 1m^3 of insulation batt with a density of 45kg/m^3, the overall carbon impact from cradle to gate (ie A1-A3) is -0.79 kgCO_2e/kg [54] (Fig. **10**).

Figure 10: Showing examples of boards, batts and quilts from biobased agri-crops straw, hemp, miscanthus. LHS Straw board from VestaEco northern Poland, Centre Miscanthus board from Miscanthus-Buscheritz east Germany and RHS Hemp batt from Senini-Tecno Canapa northern Italy [Source Author].

3.5. Medium - High Technology Developments

Some companies were noted to be active in what could be described as innovative or advanced higher technology level solutions, often requiring advanced or specialist processing or material science research and development with some companies applying raw or processed material as an additive in other materials for constructions, e.g. hemp fibres being used as a reinforcer in bioplastics and others involved in the extraction of particular elements of the raw material for application in construction, e.g. extracting miscanthus cellulose to be used for composites [55], asphalt mixtures and miscanthus lignin for applications as binders and resins, high-quality building materials, bio-composites, polymers, concrete and asphalt [56].

4. Modular System Manufacturers

Some 15 companies were identified utilising these agricultural crops / materials within modular systems, using both low – medium and medium technology levels solutions, with straw based modular solutions being dominant but also including wet based hempcrete systems and one miscanthus system found. Please see Appendix **02** for further details.

4.1. Material Basis

i) Straw

Among the modular systems straw is the dominant resource type utilised, with both low tech and low medium tech solutions being implemented. Five manufactures were focused on simple use of straw bale within a timber frame (Fig. **11**), while more common was (hand or mechanical) filling of modules with loose straw and shaving excess. Several modular companies were applying blow in chopped straw within the timber frame, a technology solution that is also being used in retrofitting of existing buildings, notably roofs.

Figure 11: Showing straw bale modular wall system in manufacture with straw bale installation LHS and complete panel RHS. Chênelet northern France [Source Author].

ii) Hemp

Hemp was the second dominant material resource among the modular systems and is being applied as wet 'hempcrete' into timber frame constructions, typically applied from a hopper into horizontally laid panels, and requiring drying time. One company utilised a hybrid wet dry approach with wet hempcrete and dry biobased construction boards, while another company developed a type of fast drying hempcrete, but non lime based, used as an infill in combination with dry biobased lining boards (Fig. **12**).

Figure 12: Showing hemp lime modular wall panel manufacturing facility, showing factory floor assembly and storage areas LHS and large complete wall panel with lifting / support frame, RHS. Wall'Up Prefa northern France [Source Author].

iii) Miscanthus

One company was sourced using a 'miscrete' from miscanthus chips and cement - as the insulative infill to a timber framed system.

4.2. System Aspects

A range of modular systems were found with distinct characteristics and a diversity of sizes, constructions, finishing etc. Generally, modules were timber frame constructions, primarily wall systems but with some producing roof and floor units.

Modules were generally load-bearing with some examples of semi structural or non-load bearing infill panels within post and beam construction. Panels had a diversity of lining boards receiving and holding a biobased insulative infill.

Most of the modular systems are dry product and application based, mainly straw, but with some examples of wet based systems, (hempcrete / miscrete), requiring drying time with production and storage impacts.

The techniques for creating hemp panels varied with some manufacturers using only a wet mix of hempcrete, others combining wet with dry biobased boards and batts, and others using specialist proprietary fast setting binders to reduce drying times.

The frame types comprised both single stud and double stud solutions, with double stud being used mainly with straw and single stud mainly with hemp.

Wall modules are generally floor story height of varying widths 600mm to 3000mm and thicknesses of 180mm to 450mm for straw panels and 300mm to 425mm for hemp panels subject to U Value requirements.

Most panel types require powered / machine lifting; however some systems are based on small module units, that facilitate simpler lifting or assisted non powered lifting methods.

Systems comprised both open (non or partially finished) elements and closed (more complete elements) for example including windows and doors or external cladding or finishes.

Small module types were generally open systems, and could be stacked, transported and lifted easier and in one case were also used in local assembly factories to compile larger and closed cell modules. See Figure **13** for overview of modular systems.

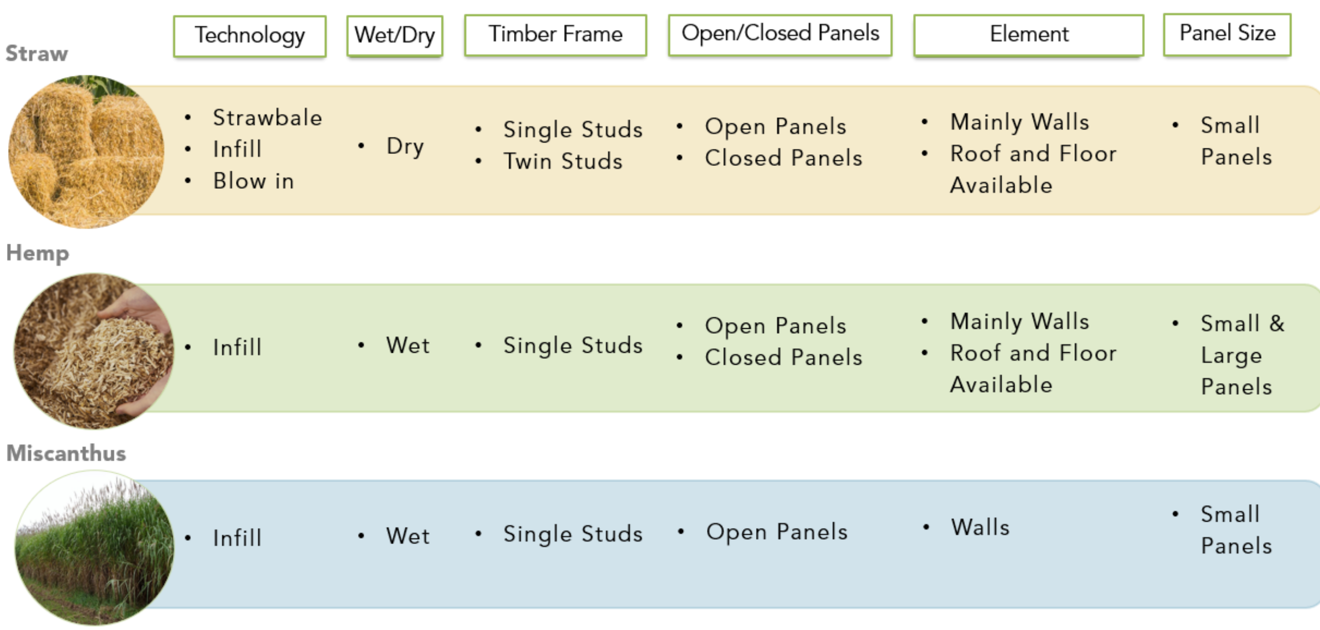

Figure 13: Provides a summary chart of the main characteristics of the modular panel system per resource type [Source Author].

4.3. Panel Performance

i) Straw

A range of modular systems were sourced utilising straw involving i) straw bale, ii) chopped straw applied in a range of ways, and iii) blow in straw. The number of companies found using these methods are 5, 3 and 1 respectively.

The standard panel height is floor height, between 2400 to 3000mm. The width varies from 850mm to 2560mm, and the thickness ranges from 180mm to 450mm.

Most manufacturers produce panels primarily for walls, but roof and floor panels are also available. The panels have density ranges from 100-150kg/m^3, with a thermal conductivity value between 0.056 and 0.068 W/mK.

A non-load/bearing wall system has been certified to fire resistance of 135 minutes [57]. Also, a load-bearing wall composed of EcoCocon straw modules with an interior clay base plaster and external wall face covered with wood fibre boards has been classified as REI (stability, integrity and insulation) 120 min in accordance with EN 13501-2:2016 [58].

The biogenic carbon content of an example average square meter of panels is 31,5 kg C/sqm and the CO_2 stored per square meter of average panel is 115,5kg CO_2 [59].

ii) Hemp / Miscanthus

Hemp panel dimensions range in height from approximately 900 to 3000mm, and in thickness from 300mm to 425mm, with width variation from large full bay widths façade panels that requires cranes or forklift for handling, while others produce smaller panels, around 600mm wide, that can be handled manually in some cases.

The thermal conductivity values are ranging between 0.052 up to 0.064 W/mK with a density range of 254 to 328 kg/m^3.

Raw hempcrete demonstrates flame integrity and thermal insulation for 240 minutes, which allows it to be classified EI (integrity and insulation) 240 [60]. Meanwhile, another manufacturers using other binder type and dry insulation declares a REI (stability, integrity and insulation) between 30 to 120minutes, subject to internal finish [61].

For a standard wall component measuring 600mm in width and 345mm in thickness, constructed from 15mm of wood wool, 175mm of bio-composite (shivs and binder), and 80mm of rigid wood fibre, the carbon cradle to gate has been shown as negative value of 51.2 kg CO_2eq, excluding cladding [61].

Regarding miscanthus, one company was found, producing panels using a mix of 90% miscanthus and 10% cement with water. These panels are allowed to dry for approximately 21 days, achieving thermal conductivity values between 0.07-0.14W/mK and densities ranging from 300 to 1200 kg [62].

4.4. Building Applications

These systems are being applied in a range of building types mainly domestic but including non-domestic and multi-story solutions, subject to regional or national regulations.

5. Summary - Key Findings

This research, while being non exhaustive and limited in geographical (European) and resource scope (straw, hemp and miscanthus), has provided insights into the state of play of agricultural crops biobased construction materials, products and systems in commercial application across Europe.

While the study assessed commercial activity by number of companies and not volumes, it is arguably still indicative of significant innovation and development in the sector with some 46 companies active in the supply of materials and products and an additional 15 active in manufacture of modular systems.

5.1. Materials and Products

Of the companies reviewed, most solutions were non load bearing materials and products across of range of technology 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 tech solutions like wet hempcrete infill and blow in straw, and a range of medium technology 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, 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.

5.2. Modular Systems

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 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.

5.3. Commercialisation

The state of play has shown that despite the barriers and challenges discussed in the literature, there is an emerging and growing biobased construction sector.

These companies have developed a diverse range of materials, products and modular systems under different technology – complexity levels, for application mainly in framed construction, but including some masonry examples, being applied in a diversity of building types, including multi story.

The key generic advantages claimed are circular biobased materials, carbon sequestration, good thermal performance including thermal buffering and moisture regulation / breathability.

Companies have secured various certifications, such as European CE Marking, requiring significant material, product and system performance testing under various harmonised, technical or national quality standards. Several companies have also developed EPD’s profiling the environmental and carbon impacts of their product.

These companies are operating locally, regionally, nationally and in some cases internationally, across a range of diverse supply chains but report challenges in relation to transport costs and to trading across Europe due to diversity of regulation and even testing standards and performance requirements in different EU countries.

6. Conclusion

This research has identified that specific agricultural crops, straw, miscanthus and hemp, are being commercially utilised in a range of biobased materials, products and modular system solutions within the construction sector, at different technology levels from low simple to advanced / complex.

The research is evidence of innovation and commercial development of biobased construction materials, products and systems, which could have significant carbon offset and sequestration benefits if further mainstreamed, as well as other environmental, social and economic benefits.

Further research could support the potential for expanding and optimising these solutions notably, improving and enhancing performance, removing and overcoming barriers – including knowledge basis, streamlining processing and manufacture, and upscaling of supply chains, greater market penetration, harmonisation of regulatory testing requirements for greater mainstreaming potential, and optimisation and expansion of agricultural resources for enhanced utilisation.

Conflict of Interest

No potential conflicts of interests are reported by the authors.

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Author’s Contribution

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

PGB: Research assistant; supporting in investigation, analysis, data collation, visualisation, drafting input and bibliography.

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Appendix 01: Material and Product Specifications

The table below summarizes the specifications of biobased insulation materials and products across Europe, derived from three primary resources: straw, hemp and miscanthus. This summary is part of a broader matrix that has been simplified for clarity, using a range of values to compile data from various companies.

	Product	Components	Wet/Dry M.P[1]	Wet/Dry C.A[2]	Dimensions[3]	Application	Thermal Cond.[4]	Density[5]	Fire[6]
LOW TECH	Straw bales	Straw position 90° stalk orientation.	Dry	Dry	L: 800-1200mm H:357-380mm W:460-510mm	Mainly new walls one off dwellings	0.043 W/mK	95-120 kg/m³	Class E to EN 13501-1:2009
LOW-MEDIUM TECH	Blow in straw	Chopped and clean straw.	Dry	Dry	Variable	New build and retrofit, walls roof and floor.	0.041-0.058 W/mK	105-141 kg/m³	Class E to EN 13501-1:2009
	Hempcrete	Composite of hemp shiv, binder and water.	Wet	Wet	Variable	New build and retrofit, non-loadbearing walls roof and floor.	0.048-0.054 W/mK	100-175 kg/m³ (dry)	B,s1-d0
MEDIUM TECH	Straw boards	Straw fibres, cellulose fibres, BICO fibres.	Wet& Dry	Dry	L: 1200-3200mm H:600-800mm W:15-120mm	Thermal and acoustic insulation for timber frame structures.	0.049-0.099 W/mK	240-379 kg/m³	Class E to EN 13501-01
	Straw batts	Straw and PMDI resin.	Wet	Dry	L: 600-1200mm H:400-1000mm W:40-200mm	Insulation between rafters and as infill of walls or slabs.	0.037-0.049 W/mK	50-240 kg/m³	Class E to EN 13501-01
MEDIUM TECH	Masonry blocks	Hempcrete mix, pressed and dried.	Wet	Dry	L: 300-600mm H:145-300mm W:60-400mm	New build walls, external and internal insulation.	0.070-0.187 W/mK	300-1100 kg/m³	B, S1, d0 (NF EN 13501-1) without render
	Hemp boards	Hemp shivs, binder (clay/lime) and water.	Wet	Dry	L:1200-2400mm H:600-1200mm W:10-60mm	Interior lining, enclosure panels, interior and exterior.	0.090-0.165 W/mK	350-1000 kg/m³	B, S1, d0 (NF EN 13501-1) without render
	Lighter Hemp boards	Hemp fibres, treated with soda as fire retardant and binding agents.	Dry	Dry	L: 600-1200mm H:600-800mm W:20-160mm	External insulation walls, panels, cavity wall and roof and attics.	0.038-0.044 W/mK	60-145 kg/m³	Class E as per DIN EN 13501 -1 (normal inflammable)
	Hemp batts	Hemp fibres, binding agents and ammonium phosphate (use as a flame retardant)	Dry	Dry	L: 600-1200mm H:370-625mm W:30-220mm	Roof, walls and floor insulation for both new building and renovations.	0.040-0.041 W/mK	35-60 kg/m³	D-s1, d0 EN 13 501-1
MEDIUM TECH	Hemp Quilts	Hemp fibres (80-90%) and binders.	Dry	Dry	L: 1100-1200mm H:370-600mm W:20-200mm	Roof insulation between rafters, wooden floors and ceilings, suspended soffits, partition walls and cavity walls.	0.039-0.041 W/mK	20-40 kg/m³	Class E (EN 13501-1 + A1)
	Miscanthus boards	Miscanthus shivs and cement bonded	Wet	Dry	L: 500mm H:500mm W:70mm	Insulation	0.072 W/mK	320 kg/m³	
		Miscanthus shivs and eco-glue bonded	Wet	Dry	L: 500mm H:500mm W:70mm	Insulation	0.045 W/mK	125 kg/m³	

L: Length; **H**: Height; **W**: Width.

[1]Material and products have been categorized based on dry or wet manufacturing processes.
[2]Material and products have been categorized based on dry or wet construction application.
[3]Dimensions have been summarized as a range between different manufacturers.
[4]Thermal conductivity has been summarized as a range between different manufacturers.
[5]Density has been summarized as a range between different manufacturers.

Appendix 02: Modular Panel Specifications

The table below summarizes the specifications of biobased modular panels across Europe, derived from three primary resources: straw, hemp and miscanthus. This summary is part of a broader matrix that has been simplified for clarity, using a range of values to compile data from various companies.

Resource	Components	Wet/Dry M.P[1]	Wet/Dry C.A[2]	Dimensions[3]	Application	Thermal Cond.[4]	Density[5]
Straw	Straw bale/ Straw infill/ Blow in straw	Dry	Dry	H: 800-3000mm W: 490-2900mm T: 180-450mm	Mainly new walls/floor/roof and some wall retrofit panels.	0.050-0.059 W/mK	100 kg/m^3
Hemp	Hempcrete mix/Hemp and binder+dry insulation layers/hempcrete+dry insulation layer	Wet & Dry	Dry	H: 900-3000mm W:600-6000mm T:300-541mm	Mainly new walls/floor/roof	0.051-0.058 W/mK[6]	254-328 kg/m^3
Miscanthus	90% miscanthus, 10% cement and water	Wet	Dry	H: variable W:variable T: 300mm	Mainly new walls	0.070-0.140 W/mK	300-1200 kg/m^3

H: Height; **W**: Width; **T**: Thickness
[1]Material and products have been categorized based on dry or wet manufacturing processes.
[2]Material and products have been categorized based on dry or wet construction application.
[3]Dimensions have been summarized as a range between different manufacturers.
[4]Thermal conductivity has been summarized as a range between different manufacturers.
[5]Density has been summarized as a range between different manufacturers.
[6]Hemp panels with an added layer of dry insulation could enhance thermal conductivity by increasing the thickness of that layer.

In terms of product fire classification testing is standardized using EN 13501-1: Fire classification of construction products and building elements. Comparison to alternative BS 476 Classification is noted in following excerpts from Irish Building Regulations. (Government of Ireland, 2024).

Table 28 Reaction-to-fire Classifications	Para 7.0.3.1
Reaction-to-fire classification to I.S.EN 13501-1	**Reaction-to-fire classification to BS 476 – 4, 6, 7, 11**
Class A1	Non-combustible materials[(1)]
Class A2	Material of limited combustibility[(2)]
Class B	Class 0
Class C	Class 1
Class D	Class 3

Notes:

[(1)]See Annex A, A10
[(2)]See Annex A, A9
[(3)]Products classified to I.S.EN 13501 do not automatically equate with classifications to BS 476, and vice-versa. Therefore, products cannot be assumed to have European class or BS 476 class unless they have been tested and classified accordingly.

Appendix 03: List of Analysed Companies, Including those Manufacturing Materials, Products and Modular Panels.

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
ISTRAW	www.istraw.tech
KINGSPAN	www.kingspan.com
KOBE	www.kobe-cz.eu
LA CHANVRIERE	www.lachanvriere.com
LOPAS	www.lopas.at
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
PAILLE-TECH	www.pailletech.be
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